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(U) TEXTILE TECHNOLOGIES INC HATBORO PA*
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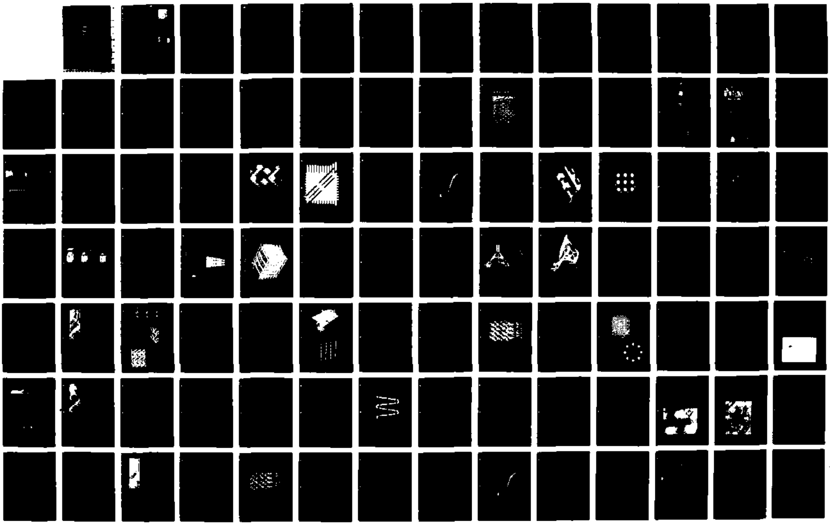

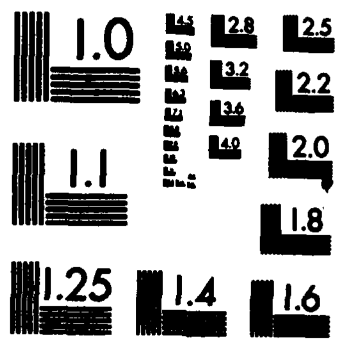
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ASSESSMENT OF ANGULAR WEAVING FOR TURBINE COMPONENTS

Marilyn J. Jupina and Ted Lynch

Textile Technologies, Inc.
Hatboro, PA 19040

January 1987

Final Report for Period June 1986 - January 1987

Approved for Public Release; Distribution Unlimited

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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NOTICE

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS: NONE

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for Public Release; Distribution Unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFWAL-TR-87-2027

6a. NAME OF PERFORMING ORGANIZATION: Textile Technologies Inc

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION: Aero Propulsion Laboratory (AFWAL/POTA) Air Force Wright Aeronautical Laboratories

6c. ADDRESS (City, State, and ZIP Code): Hatboro PA 19040

7b. ADDRESS (City, State, and ZIP Code): Wright-Patterson AFB, Ohio 45433-6563

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-86-C-2651

8c. ADDRESS (City, State, and ZIP Code)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
65502F	3005	20	51

11. TITLE (Include Security Classification): Assessment of Angular Weaving for Turbine Components

12. PERSONAL AUTHOR(S): JUPINA, Marilyn J.; LYNCH, Ted

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 86Jun23 TO 87Jan23

14. DATE OF REPORT (Year, Month, Day): 1987 January 23

15. PAGE COUNT: 103

16. SUPPLEMENTARY NOTATION: This is a Small Business Innovation Research Program, Phase I

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
11	05	
21	05	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Fiber Weaving, Angular Weaving, Composite Components, 3-Dimensional Weaving, Gas Turbine Engines

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report evaluates the ability of current textile weaving looms to manufacture fiber pre-forms for composite components of gas turbine engines. It is concluded that no current loom has the capability to automate the fabrication of components with angular fiber orientation coupled with through-the-thickness reinforcement. The company intends to pursue the design of such a 3-dimensional loom through a separate contract.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: RAYMOND P. BULL, Sqn Ldr, RAF

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22c. OFFICE SYMBOL: AFWAL/POTA

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

PROJECT SUMMARY

"The Assessment of Angular Weaving for Turbine Components" Phase One Final Report is an evaluation of the ability of state-of-the-art textile fabrication techniques to cost effectively manufacture high quality fiber preforms for composite turbine engine components. Of the myriad of textile processes available, the following were selected for indepth investigation: conventional weaving, jacquard technology, multidirectional weaving, "through-the-thickness"™ braiding, triaxial weaving, multiaxial warp knits and lappet weaving. These technologies offer the ability to orient off-axis fibers, produce multiple layers, fabricate complex fiber architectures, and accommodate high modulus fibers designed for polymeric, metal and ceramic matrix systems. It was determined that no one technique could provide all of these capabilities.

Therefore, if composite turbine engine components are to be preformed, a new loom is required. It may be possible to draw together the technologies investigated to in effect extract the best of each to build such a loom. This loom would have a jacquard-type warp control system, diagonal yarn control provided by the lappet wheel system and rapier fill yarn insertion in order to weave complex fiber architectures.

The resulting preforms would have to be carefully designed to be compatible with state-of-the-art matrix impregnation systems. The hypothetical loom referenced above, the fiber architectures and the impregnation technique, would have to be designed to account for this synergism.

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THE ASSESSMENT OF ANGULAR WEAVING
FOR TURBINE COMPONENTS

I. INTRODUCTION

This document constitutes the final report to the Air Force Aero Propulsion Laboratory for SBIR Phase One No. F33615-86-C-2651, entitled, "The Assessment of Angular Weaving for Turbine Components". This report presents a study of state-of-the-art textile fabrication techniques for composite structures for engine component application. Polymeric, metal and ceramic matrix systems were addressed. Section II describes the development of the turbine engine. Section III equates the benefits of polymeric, metal matrix and ceramic composites for turbine engine components. Sections IV and V review and assess state-of-the-art textile fabrication techniques. Section VI discusses specific applications of fiber reinforced composites for turbine engine components suggested by major turbine engine manufacturers. Finally, Section VII presents the conclusion.

II. TURBINE ENGINE DEVELOPMENT

Jet power as a means of propulsion has been known for hundreds of years, although its use for propelling vehicles that carry loads is comparatively recent. The earliest known reaction engine was an experimental, steam operated device developed about the 3rd century BC by the Greek mathematician and scientist Hero of Alexandria. Known as the aeroliopile, Hero's device did no practical work, although it demonstrated that a jet of steam escaping to the rear drives its generator forward. The approximate operating temperature of the aeroliopile was 212 F.

In 1910, seven years after the Wright brothers flights, the French scientist Henri Marie Coanda designed and built a jet-powered biplane, which took off and flew under its own power with Coanda at the controls. Coanda used an engine that he termed a reaction motor. He later abandoned this work due to the lack of public acceptance of his aircraft. It was not for another twenty years that Sir Frank Whittle outlined the first practical form of the modern gas turbine. In 1935, Whittle applied his basic design to the development of the W-1 turbojet engine, which made its first flight in 1941.

Obviously great progress has been made since the days of Hero and Whittle. Todays engines are far superior to those used just 30 years ago. The F404 turbofan engine used to power the current F-18 fighter is far different than the J79 that powered the F-4 built in 1958. Both engines have approximately the same thrust, but the F404 has twice the pressure ratio produced by only half the number of compressor stages; has half the engine weight;

three-quarters of the length; and 80% of the frontal area. Also, from a cost perspective, the F404 achieves this thrust with 7700 fewer parts.

Advanced aircraft engines require advanced materials to meet their goals of performance, thrust-to-weight ratio improvement, and fuel efficiency. Fiber reinforced composite materials offer the opportunity for gains in performance and weight reduction through the development of stiffer, stronger and lighter weight materials capable of withstanding higher operating temperatures. A target temperature of 4000 F has been identified. This represents a major leap forward when compared to present day turbojet engines (1815 F) and certainly would amaze the likes of Hero of Alexandria.

The need for composite materials and processing development of advanced turbine engine components has been addressed in numerous government-funded studies. It is obvious to many that the aircraft of the future, that is, the Advanced Tactical Fighter (ATF), the Advanced Tactical Aircraft (ATA), the National Aerospace Plane (NASP) amongst others, will all require engines far more advanced than those in the inventory today. These engines will be required to run at greatly increased operating temperatures.

There is a great deal of work going on at this time to advance the state-of-the-art of turbine engine materials. For example, research is progressing in the application of graphite/polyimide composites to engine components. General Electric has designed and fabricated an inner cowl for an experimental engine called QCSEE (Quiet Clean Short-Haul

Experimental Engine) developed under a NASA-Lewis contract. The cowl, which has a maximum diameter of 35.8 inches, was autoclave fabricated using Thornel 300 graphite fabric, and PMR 15 polyimide resin. After more than 300 hours of ground testing, this part showed no apparent degradation. This successful design, fabrication, and testing effort established the feasibility of using high temperature polymer composites for large engine static structures. General Electric has also demonstrated this feasibility in the fabrication of the F-110 engine inner duct of graphite/polyimide composites while under contract to the Air Force.

Work is ongoing at a far less mature level involving the development of high temperature composites designed for use in the hot section of the turbine engine. Metal matrix composites (MMC) using magnesium, aluminum, titanium, and superalloy matrices are being developed for application to static and rotating engine components. Silicon carbide fiber reinforced titanium low pressure spool shafts are being developed for turbine engines. Higher temperature MMC's for use as turbine blades and vanes are being studied. They utilize superalloy matrices such as Fe-Cr-Al-Y.

Ceramic composites hold great potential for use in turbine engines. Monolithic ceramics display outstanding thermal properties but are substandard in the areas of toughness and reliability. It may be possible to surmount these hurdles through the reinforcement route. This approach is driving developers towards improved carbon-carbon composites as well as fiber

reinforced silicon carbide.

The High Temperature Initiative presently underway at the Air Force's Wright Aeronautical Laboratory stresses the development of materials, specifically composites, for use in turbine engines. If the goal of inclusion of composites in turbine engines is to be attained, it will be necessary to significantly advance the state-of-the-art of composite manufacturing. The current processes in use in thermoset composite structure fabrication are just not suited to the fabrication of large quantities of reliable, high quality engine parts. The present techniques utilized in the fabrication of MMC's are labor intensive, prone to large variations in part quality and definitely not suited to the production of thousands of engine parts.

If advances are to be made in these areas, it is obvious that fiber positioning must be advanced. The structural designer is better able to design composite materials through the use of more sophisticated computer programs. He is able to produce designs which efficiently use the properties of the fibers and the matrices loads transmission properties. The materials scientists are able to identify composite systems with the chemical, thermal and mechanical properties required to meet the harsh environment of the turbine engine. But these advances are of little use if the fabricator is not able to position fibers in the manner called for by the designer and unable to do so cost effectively and without degrading the properties of the fibers as called for by the materials scientists. This is the crux of the dilemma identified in this effort. Singled out as the only possible solution to this problem, the textile ergineer must bring to bear

his expertise. Textile engineers are charged with the job of placing fibers of all kinds in exact positions without causing damage to the fiber. This positioning must be done cost effectively and in a highly repeatable, reliable fashion. This set of goals applies to all of the products produced by the textile engineer whether they be clothing or fabrics to be prepregged for eventual use in fabricating structures for a fighter aircraft. The turbine engine represents a unique challenge to the textile engineer in that the hardware must be fabricated from fibers that are extremely difficult to handle and the parts are generally complex in configuration.

This study involved the assessment of available textile technologies in light of their ability to meet the yarn positioning problems specific to the turbine engine parts. In addition, it looked at a specific part, a translating cowl of a thrust reverser, and assessed the unique needs of that piece of engine hardware. Finally, it identified the work that must be done if this shortfall in textile technology is to be relieved.

III. COMPOSITE MATERIAL BENEFITS TO TURBINE TECHNOLOGY

Advanced aircraft engines require advanced materials to meet their goals of performance, high thrust-to-weight ratio, and increased fuel efficiency. For many of the components of these advanced engines, it will be necessary to find materials that are light weight, can resist temperatures of up to 4000 F, are resistant to chemical attack, and have superior high temperature impact and creep resistance. Numerous studies run by the Air Force, the Navy and NASA indicate that the most promise class of materials for this application is the composite materials. Within this class, emphasis is being placed on carbon-carbon composites, metal matrix composites, and ceramic matrix composites.

Prior to the development of composite materials, aluminum alloys were commonly used in the production of many turbine components (i.e., compressor blades, vanes and discs). The increasing need to improve engine performance (i.e., increase Mach numbers) has reduced the number of components that can use aluminum alloys. Only components exposed to operational temperatures less than 200 degrees C can utilize aluminum. Titanium alloys have provided a material candidate which has high strength/stiffness with a considerable weight reduction at temperatures in excess of the aluminum alloy limits. Titanium alloys are now widely used in modern engines and comprise 60-80% by weight of the compressor component. Titanium alloys have a temperature capability of 550 degrees C and excellent corrosion resistance. However, titanium alloys have low creep resistance above 550 degrees C; therefore, nickel and nickel-iron alloys and

superalloys are required for the hottest compressor stages of the modern jet engine.

Engine performance has improved qreatly during the period where conventional materials such as aluminum and titanium have been used. Fiber-reinforced composite materials offer the opportunities for much further gains. The high strength/weight and stiffness/weight properties of composite materials are already being taken advantage of in primary and secondary airframe structures. Due to the fact that aeropropulsion systems present a much more hostile environment to materials than airframes, fiber-reinforced composite use there has proceeded at a much slower pace. Fiberglass/epoxy materials have been used to fabricate structural components such as fan duct fairings, shroud panels, seals and spacers. Low thermal-oxidative stability and low glass transition temperature restrict the use of fiberglass/epoxy composites to below 177 degrees C. Higher temperature resistant polymers have been developed to increase the temperature capability of polymer matrix composites. NASA Lewis developed a PMR-15 (Polymerization of Monomer Reactants) polyimide system which is currently being used by Pratt and Whitney and General Electric for higher temperature applications. At a cure temperature of 316 degrees C, this system has allowed for the fabrication of void-free composite turbine components.

The development of Metal Matrix Composites (MMC) has been directed at increased use temperature (maximum 1000 degrees F), improved toughness and ductility, and enhanced matrix-aided properties such as electrical/thermal conductivity, oxidation resistance and impact resistance. The major focus to-date has been

on aluminum matrix composites. Discontinuous SiC particulate and whiskers are being used to reinforce aluminum alloys yielding low-cost, isotropically loaded structures. Continuous monofilaments, such as boron and SiC and multifilament yarns, such as graphite and aluminum oxide, are being used to reinforce anisotropic, high performance aluminum matrix composites (e.g., Boron/Al fan blades). Magnesium matrices are also being developed for reinforcement with graphite, for applications where high specific stiffness and a zero coefficient of expansion is required. Magnesium and its alloys are very attractive matrices for their low density, high performance and relative ease of casting compared to other metal based systems. Graphite, boron and alumina fiber reinforced magnesium have been successfully demonstrated. Aluminum and magnesium based MMC are limited to lower temperature regimes.

Titanium alloys have unique properties such as high strength, high resistance to corrosion in severe atmospheric condition, as well as a low coefficient of thermal expansion. Composites based upon titanium and its alloys such as boron/titanium and silicon carbide/titanium are being fabricated for engine applications which require high stiffness/strength at elevated temperatures.

Superalloy matrix composites such as refractory metal wire reinforced superalloys offer a promising potential of heat-resistant composites. Refractory wires, tungsten alloy (W - 2% ThO_2) and molybdenum alloy (TZM), are potential candidates for turbine engine blade materials due to their high tensile strengths and impact resistance.

Monolithic ceramic materials offer gains in gas turbine performance due to their high melting points and oxidation resistance. However, they also possess serious limitations. These include poor thermal shock resistance, low impact strength, poor structural reliability, and/or reproducibility. For example, hot pressed silicon nitride (Si_2N_4), a candidate for use as a high temperature vane material, has excellent oxidation resistance and thermal shock resistance. However, it is limited by its relatively low impact strength. The solution to this problem may be the reinforcement of Si_2N_4 with fiber or wire, thus making a ceramic composite which provides energy absorption modes not available in monolithic materials.

Ceramic matrix composites (CMC) reinforced with low aspect ratio (length/diameter) particulate and whisker reinforcements lend themselves to conventional ceramic processing methods based on powder blending methods. This offers three-dimensional toughening and cost advantages for large volume ceramic matrix composite production such as automobile applications. However, continuous fibers have major structural advantages over particulates and whiskers. Employing continuous fibers in the CMC forces unstable matrix cracks to pass around the high modulus fiber (not through them), so that after matrix failure, the reinforcing fibers remain intact preventing castastropic failure of the composite. Further loading would allow continued matrix cracking without composite failure until the ultimate fiber strength is reached, at a far greater fracture strain than that of monolithic ceramic matrix. Due to the relative newness of CMC

materials, two areas need to be addressed:

1. The development of high strength and modulus, small diameter fibers whose properties greatly enhance the structural integrity of the composite.

2. Net shape composite processing methods which result in uniform microstructures of nondegraded aligned fibers surrounded by low porosity matrices.

To summarize, critical material needs for the development of turbine engines include:

1) Material and fabrication cost reductions to reduce acquisiton cost and life cycle maintenance costs.

2) Lighter weight materials to improve specific fuel consumption and reduce overall engine weight.

3) Materials to permit design innovations allowing for the achievement of higher performance (i.e., use of higher overall pressure ratios in the compressor stages and higher operating temperatures in the turbine stages).

4) Advanced composite materials should possess such properties as high strength/stiffness, enhanced ductility, and oxidation and thermal shock resistance.

Textile Technologies, Inc. (TTI) conducted a study to assess weaving techniques applicable to the production of turbine engine components. This effort was sponsored by the Air Force Propulsion Laboratory in 1986, Contract No. F33615-85-C-2578. It was concluded that the weaving of preforms for composite reinforcements rather than weaving of laminates can reduce fabrication costs and enhance the structural performance of production parts. Existing textile technology is examined in

light of its ability to fabricate such preforms in the next section.

IV. REVIEW OF STATE-OF-THE ART "ANGULAR" FABRICATION TECHNIQUES

Structural performance is the foremost consideration of the composite engineer, when designing a turbine engine component. The composite engineer selects a fiber reinforcement, a matrix and proposes a fiber "architecture", to meet specific design parameters. Fiber "architecture" is defined as the spatial positioning of fibers (i.e., inplane [0 degree/90 degree] and off-axis [+/-45 degree]), relative to a structural composite preform. The ability to place these fibers at specific angles provides for the tailorability of structural properties for composite materials. The composite engineer relies on the textile engineer to develop fabrication techniques which automatically and accurately place fibers in specific locations. Clear lines of communication between the composite engineer and the textile engineer are necessary to successfully execute the fabrication of high quality, critical components.

Textile machines originally designed for the manufacture of apparel fabrics are not designed to manipulate high-modulus fibers so as to create complex fiber architectures. Textile engineers have been able to modify these machines to handle these once deemed "unweavable" fibers. However, conventional textile technology (i.e., weaving) is generally limited to placing fibers in 0 degree/90 degree fiber orientaton. This limitation poses a problem when off-axis fiber orientation is required in a structural design. To address this need, several fabrication techniques have been developed to provide a mechanism to place fibers at specific angles other than 0 degrees and 90 degrees.

These state-of-the-art fabrication techniques are reviewed with respect to their applicability to the production of turbine engine components in the sections to follow:

A. CONVENTIONAL WEAVING:

State-of-the-art conventional weaving systems combine eighteenth century textile technology with avant garde computerized systems. The actual textile fabrication process remains basically the same as it was 100 years ago. Machinery modifications have been made primarily for the purpose of increasing production rates. Updating the technology by increasing machinery speeds, reducing production set-up time, and reducing machine down time has benefited the composite preform engineer. Now, it is not necessary for a preform engineer to wait literally days for design alterations to be completed. Fabric designs can be changed in minutes on state-of-the-art equipment through the liberal use of computers.

Conventional weaving consists of interlacing two sets of yarns perpendicular to each other. The 0 degree set is called the "warp" and the 90 degree set is called the "filling". The warp axis is the continuous fabric direction. Warp yarns are fed through heddles which are alternately raised and lowered for interlacing with the crossing 90 degree filling yarns. The insertion of a filling yarn is typically accomplished by one of two methods. The first method employs a shuttle, which is in effect, a bobbin that is propelled back and forth between alternately raised and lowered warp yarns, dispensing the filling yarn as it travels. With present technology, this filling

insertion technique allows for the manufacturing of 0 degree/90 degree woven tubes, shapes and integral multi-layer structures (Figure 1). The second filling insertion mechanism comprises a category of looms which do not use shuttles and are usually referred to as shuttleless looms. This type of loom may insert yarns as filling in an assortment of ways including a rigid rapier (typical in graphite weaving), a flexible rapier, a water jet, an air jet, or even by firing a tiny projectile.

Microprocessors have particularly affected the textile industry through the automation of routine operations. This has resulted in improved reliability and accuracy in producing 0 degree/90 degree woven textiles. The end result is higher production, less waste, and lower manufacturing costs.

Conventional Weaving

Advantages

- Highly Automated
- Orthogonal Structures
- High Modulus Fibers
- X-Y-Z Fiber Architecture
- High Fiber Volumes
- Low Incidence of Resin Rich Areas
- Low Production Cost Per Yard
- Moderate Production Rates

Disadvantages

- No Off-Axis Fiber Orientation
- Preform Design Limited by Number of Harnesses
- Less than .75" Fabric Thicknesses

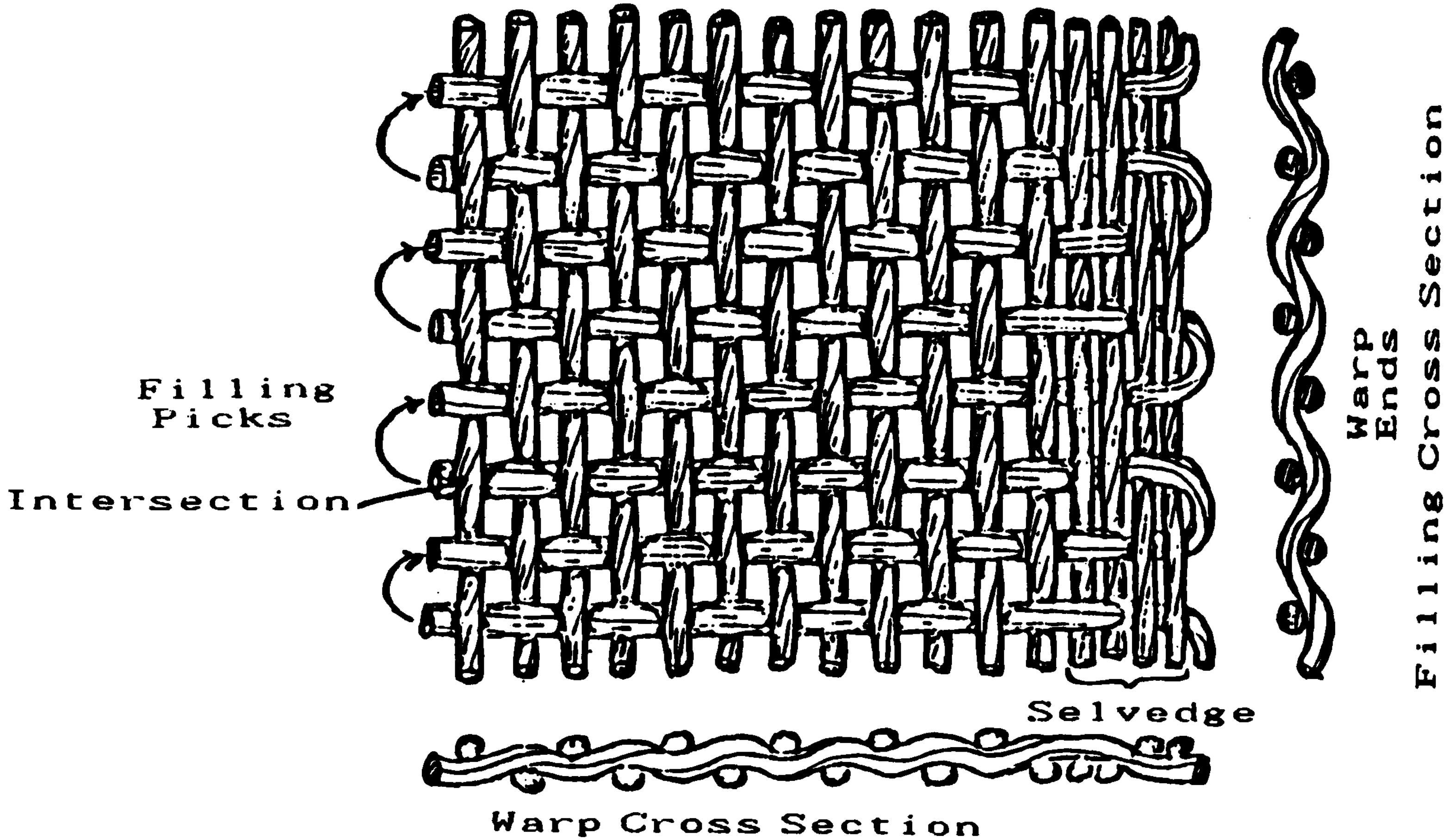


FIGURE 1 - 0°/90° WOVEN FABRIC

WEAVING PRODUCTION AIDS

Special design features are added to conventional weaving technology to increase machine efficiency. Shuttleless looms employing pneumatic and hydraulic filling insertion are able to achieve increasingly higher production rates than shuttle looms. As weaving speeds increase, the need for more precisely monitored quality control systems arise. Major loom manufacturers consistently address this topic by implementing yarn draw-off testers and filling simulators, electronic pick out and insertions, automatic pick finding devices and yarn tensioning devices. "Tensocan" is one of many devices designed to aid weaving by checking the tension of individual yarn ends during the entire weaving process. Multiple shed looms which allow for simultaneous shed formation are currently in operation dramatically increasing production rates.

JACQUARD TECHNOLOGY

Textile composite engineers know the limitations of conventional weaving technology with respect to weave configurations. Conventional looms, whether shuttle or shuttleless, employ harnesses to group the zero degree or warp yarns in the loom. A typical, highly automated, loom would be limited by the amount of harnesses it may have, generally 24. This translates to a weave configuration confined to a repeat of 24 different orders of interlacing. Therefore, if complicated structures are to be woven on a loom, the textile engineer must turn to a "harnessless" loom.

The Jacquard shedding motion was invented in the 18th century by Joseph Marie Jacquard in Lyons, France. Jacquard fabrics are known for being the most difficult and labor intensive to produce of conventional weaving technologies. Some testify to the fact that "for not the Jacquard - there would be no computer". Bascially, the Jacquard has the ability to control the raising and lowering of individual warp ends. Therefore, a fabric design is only limited in repeat by the amount of ends a Jacquard can control, referred to as the number of hooks.

The mechanism of a Jacquard is complicated in effect. Each warp end is controlled by an individual harness cord hanging vertically from a frame suspended above the loom. The harness cords have a lingoe attached to the lower extremity which with gravity act as a weight. The harness cords are threaded through a comberboard that organizes their positions (Figure 2). Each harness cord is then knotted to a neck cord. This knotting sequence can be a 2:1, 3:1 and up to 8:1 relationship depending on the amount of ends to be individually controlled in the loom. For example, a 2:1 tie would yield half the amount of total ends controlled in the loom, giving two design repeats. Each neck cord is attached to a hook, that passes through a grate, which neatly positions the hook. The hooks at their highest point rest on griff blades, the hooks are held by needles. The needles horizontally positioned, are threaded through a needle board and come in contact with a card cylinder (Figure 3).

As the card cylinder rotates, a card with a system of blanks and holes respective to the arrangement of needles in the machine

1. griff blades
2. card cylinder
3. hooks
4. grating
5. neck cords
6. harness lines
7. comber board
8. top loops
9. mails
10. bottom loops
11. lingoes

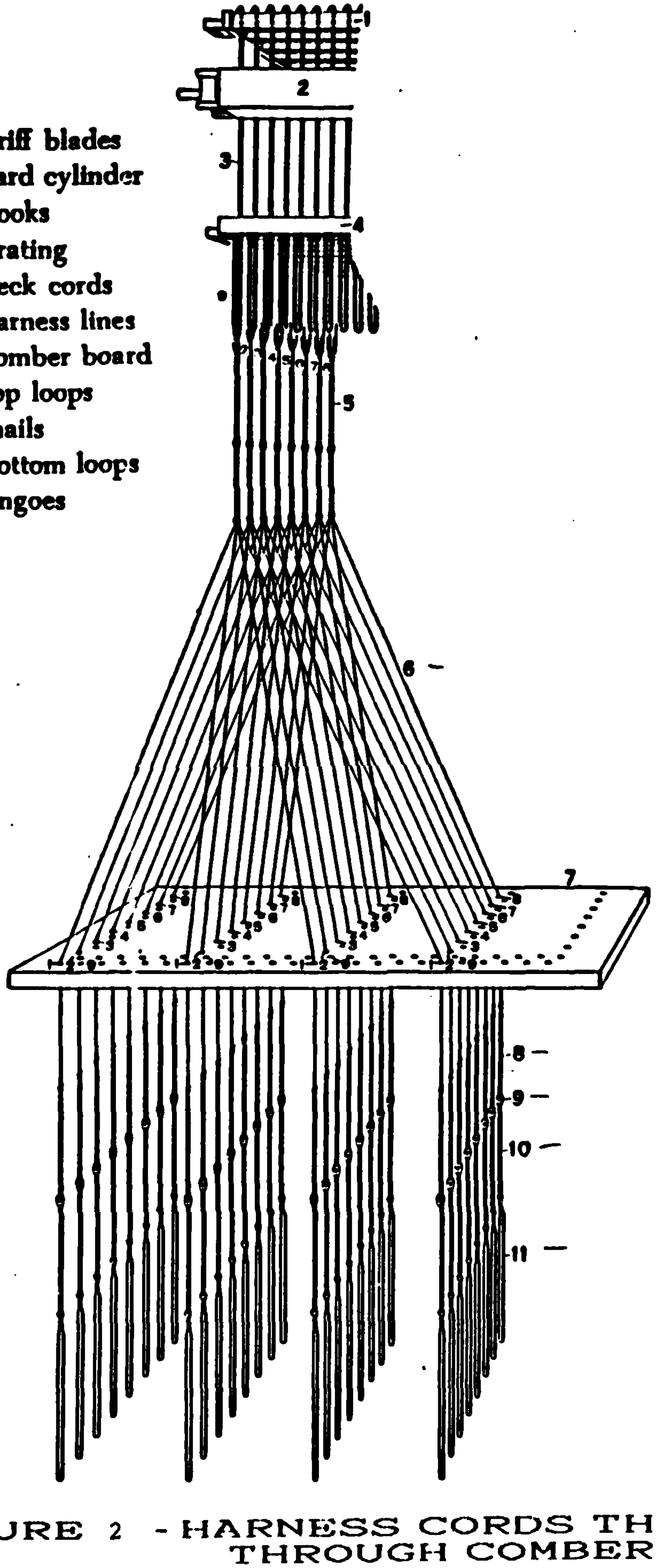
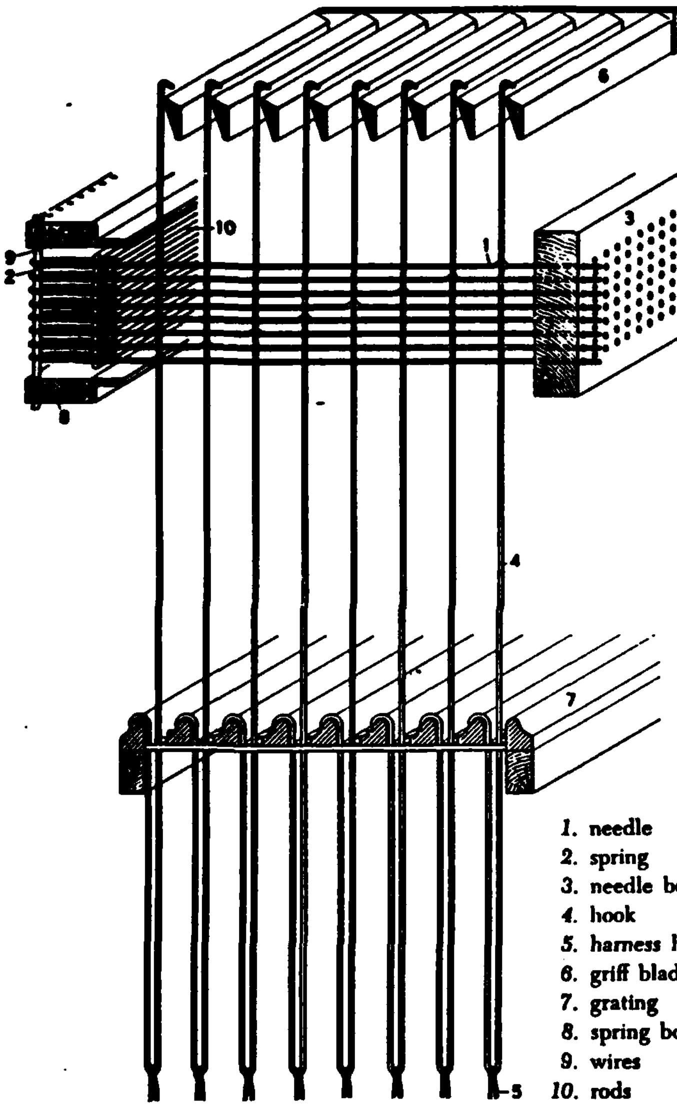
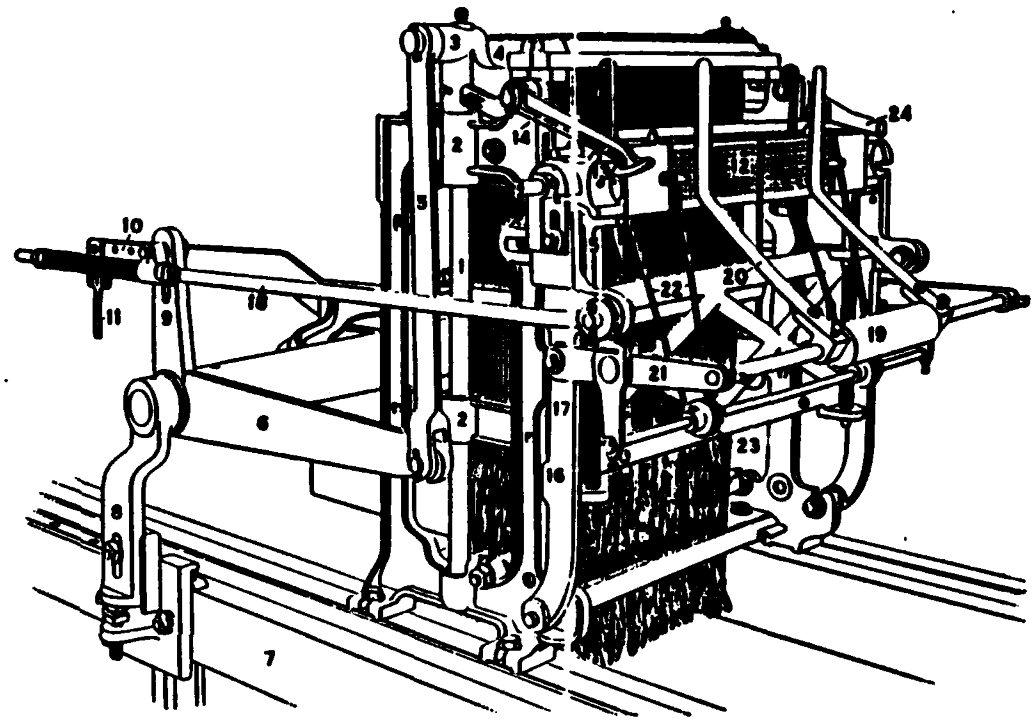


FIGURE 2 - HARNESS CORDS THREADED THROUGH COMBERBOARD



1. needle
2. spring
3. needle board
4. hook
5. harness line
6. griff blade
7. grating
8. spring box
9. wires
10. rods



1. upright shaft
2. slide bearings
3. bracket
4. casing
5. vertical arm
6. elbow lever (long arm)
7. supporting beam
8. adjustable bracket
9. elbow lever (short arm)
10. short horizontal arm
11. drive rod
12. cylinder
13. lantern
14. pawl
15. hammer
16. hammer spring
17. batten
18. connecting rod
19. roller
20. flat springs
21. roller bracket
22. band
23. whorl
24. safety pawl

FIGURE 3 - NEEDLES COME IN CONTACT WITH CARD CYLINDER

comes in contact with the needles. The direct relationship between the needles and the card cylinder is the essence of the Jacquard motion. A hole in the card will allow the needle to pass through, therefore not hindering the position of the hook over the griff blade. Conversely, a blank in the card butts the needle and pushes it laterally along with the hook, which now jumps from over the griff blade, and descends (Figure 4). The descent of the hook, now attached to the warp end, causes the warp end to be lowered. A hole in the card translates to a raised warp end. Jacquard is a system of selectively raising and lowering individual warp ends through the use of a cylinder reading a punched card.

COMPUTERIZED JACQUARD

The Jacquard system has translated very well into computer aided weaving technologies. Microprocessors and VDU's (Video Display Units) replace the traditional and laborious method of preparing a Jacquard design. Several manufacturers have engineered systems which allow for instantaneous weave configuration set-up and alteration. Gemweave and Weavette are two computer aided Jacquard design systems currently in operation in the industry.

GEMS of Cambridge, Ltd. in conjunction with J & J Cash, of Coventry, introduced the Gemweave system for the design and production of Jacquard paper cards. The Gemweave system utilizes a microprocessor controlled unit that converts data from the computer into a form that can operate a modern Jacquard paper punch machine. The Gemweave hardware consists of four separate

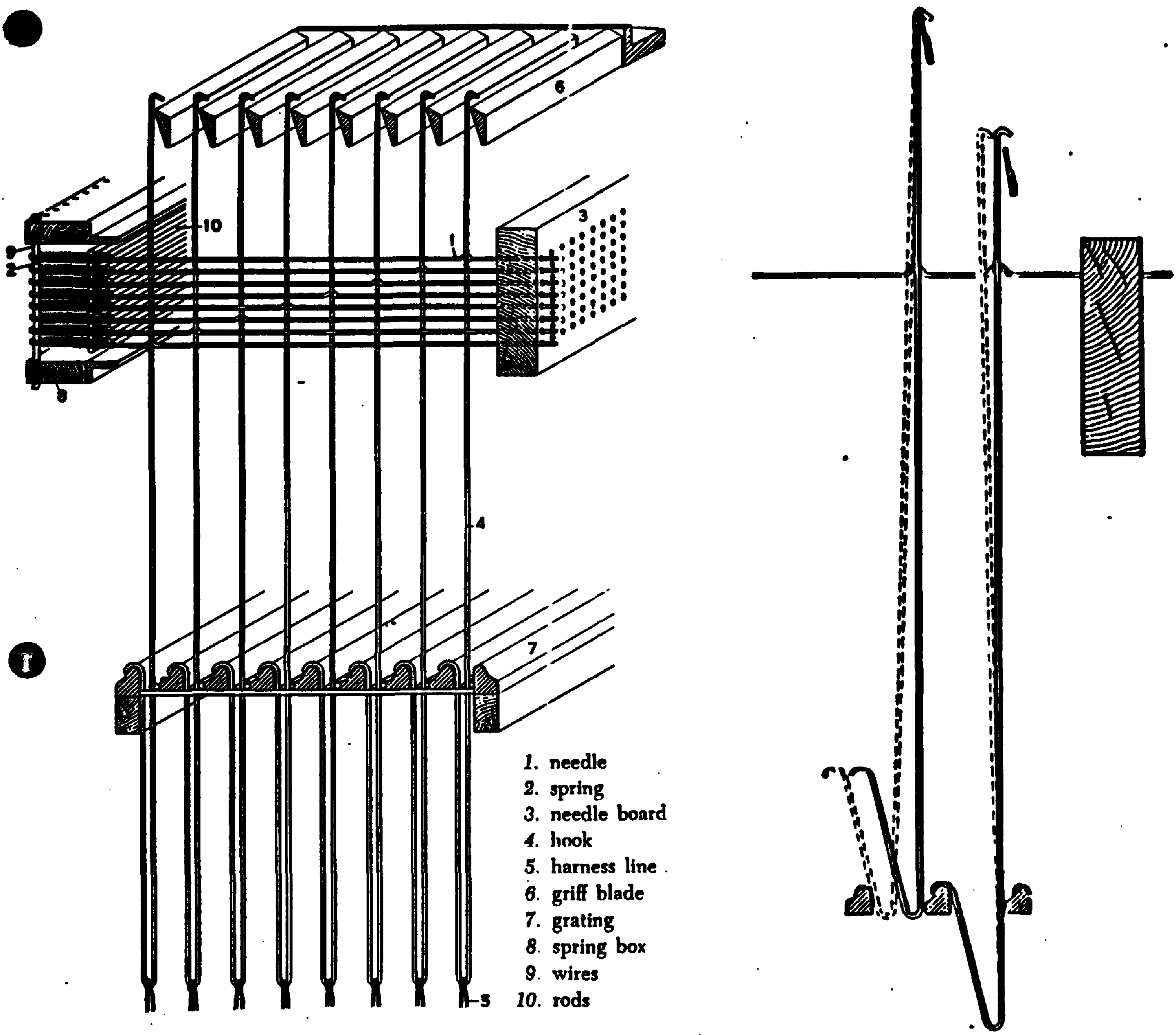


FIGURE 4 - HOOK JUMPS FROM GRIFF BLADE

modules: the central controller, the workstation, the high resolution scanner and the card punch/controller. Fabric patterns can be designed directly on the color monitor or fabric structures can be digitally scanned. An extensive range of software is available to facilitate creating or modifying designs in the pattern store. The card punching station takes design information direct from the pattern stores and translates this into a punched card format by a microprocessor driven high speed Jacquard card punch.

Weavette from Viable Systems is a specialized Jacquard pattern design CAD/CAM based workstation. It consists of a digital imaging camera for entering pattern designs, a pattern editing station, an endless paper punch station and a magnetic tape archival system. The Weavette system works on the same principle as the Gemweave system.

Several options available on the Weavette system allows it to accommodate different Jacquard design feed systems. Older Jacquards utilize the card punch system. Whereas newer Jacquards employ continuous punched paper and the state-of-the-art equipment installs a direct interface to the loom (EPROM). All three of the above Jacquard fabric manufacturers could incorporate the Weavette into their systems.

In the summer of 1987, Textile Technologies, Inc. will install a highly specialized Jacquard system. The weaving apparatus was designed primarily for weaving x,y,z fiber preforms for composite applications. Its innate capabilities include: the ability to weave high modulus yarns, to obtain multi-layer x-y-z

fiber orientation in complicated fiber architectures (such as "hat" panels), and the ability to alter or completely change woven structural designs automatically. This Jacquard system in controlling over 2000 ends individually will possess a vast potential for fabricating complicated woven preforms for composite application.

The computer has allowed the textile industry the flexibility to change according to market demands, rather than to play catch-up. The ability to input pattern designs digitally, edit electronically and directly interface with the loom to output (weave) these patterns is quite an advancement.

Jacquard Technology

Advantages

- Automated Weaving
- 3-D, X-Y-Z Yarn Systems
- High Modulus Fibers
- Near-Net Shape Preforms
- Moderate Production Rates
- Extreme Weave Configuration Flexibility
- High Fiber Volume Percentages
- Resin Rich Areas Unlikely
- Moderate Production Overhead
- Ability to Tailor Width During Weaving
- 1.5 Inch Fabric Thickness and Less

Disadvantage

- No Off-Axis Fiber Orientation

Computerized Jacquard Systems yield all of the above considerations, and in addition, can edit and change weave configurations instantaneously.

B. FORGOTTEN TEXTILE SYSTEMS:

Weaving technologies that otherwise may be deemed antiquated can offer solutions to the need for off-axis fiber orientation in woven fabrics. Lappet weaving interweaves auxiliary yarns into a base fabric construction in other than 0 degree/90 degree configurations. Schiffli embrodiery machines stitch yarns into a base fabric as a patterning device. These methods, although never employed for fiber preforms can offer technologies relevant to the new concept of multi-angular weaving.

Lappet weaving introduces an extra warp to a ground fabric for figuring effects. The whip threads, acting as the additional warp, are selectively stitched into the ground fabric. The stitching action is more readily defined by the whip thread being woven into the base fabric structure at a predetermined interlacing of filling with warp (Figure 5). It is the primary function of Lappet weaving to create a whip thread horizontal float.

Pattern wheels govern the lateral movements of the whip threads. Two types of pattern wheels exist: the common wheel and the presser wheel. It is possible through the presser wheel system to move a whip thread in the same direction on succeeding picks - forming lines in a diagonal direction across the cloth (Figure 6). This capability by definition yields a base fabric with auxiliary yarns oriented at off-axis angles.

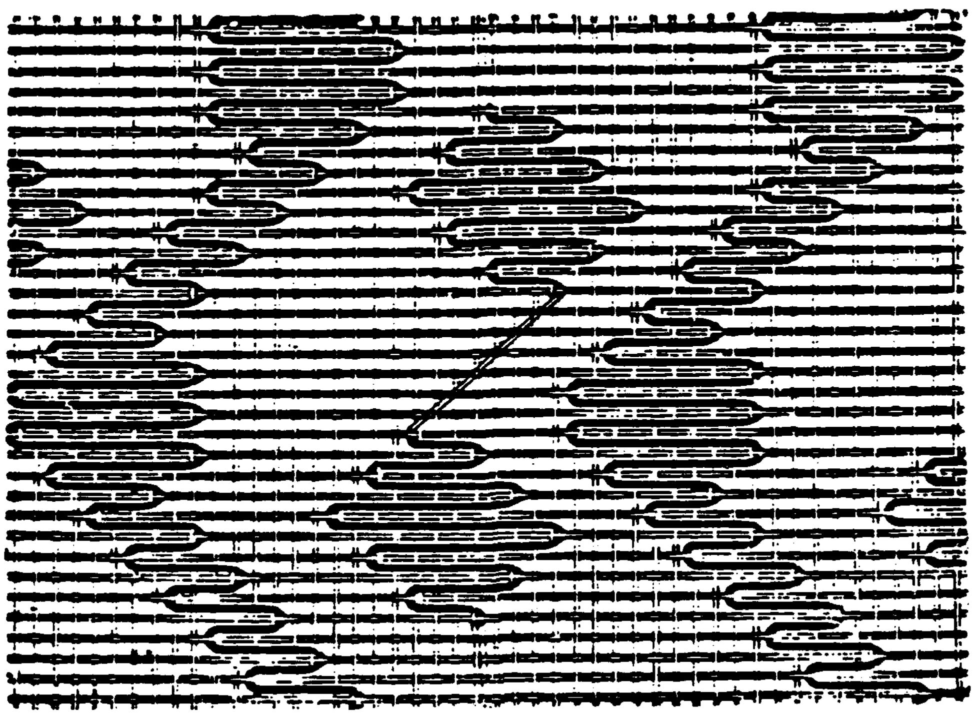


FIGURE 5 - WHIP THREAD INTRODUCTION TO BASE FABRIC

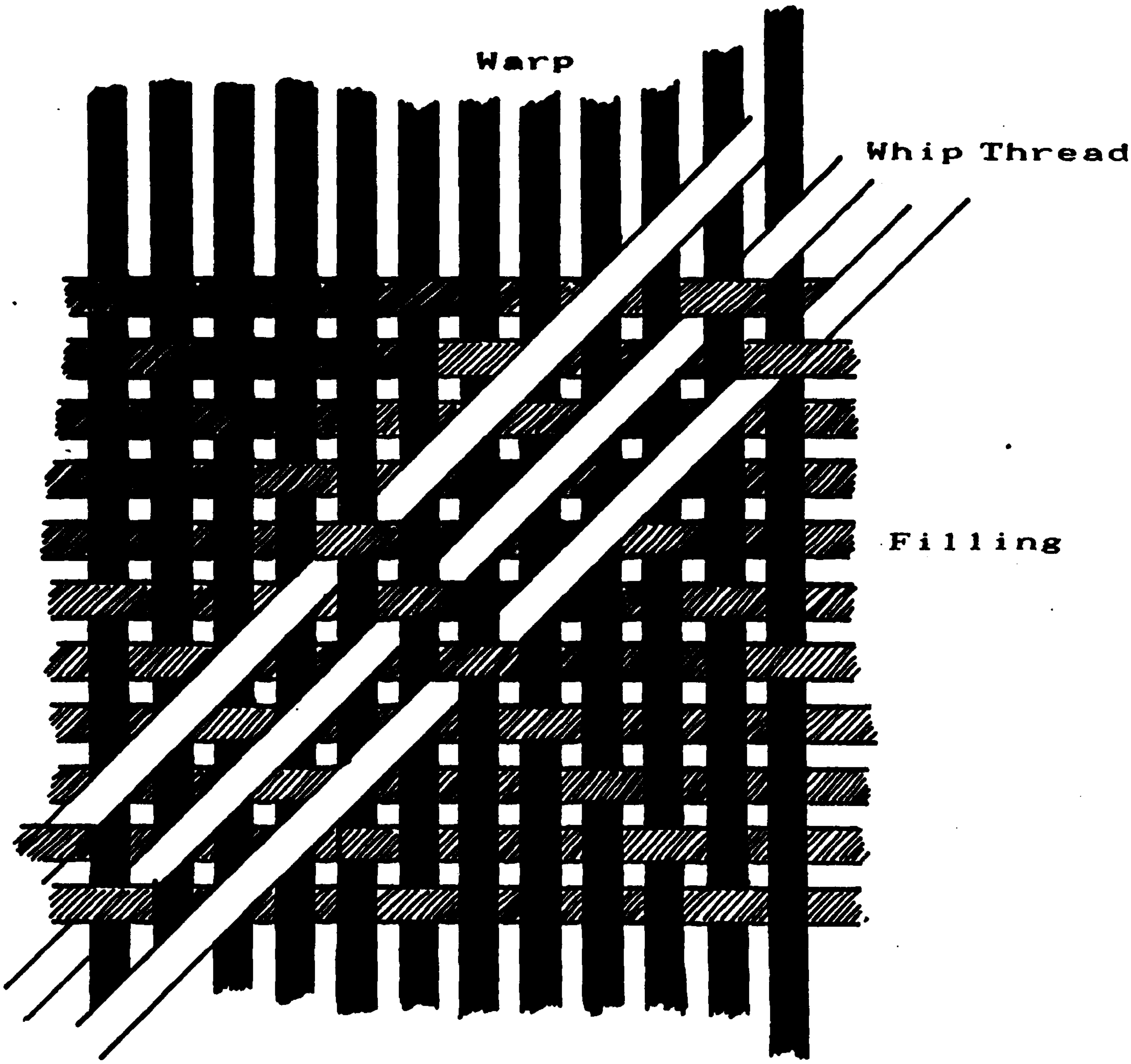


FIGURE 6 - DIAGONAL WHIP THREAD

Schiffli embroidery machines also introduce auxiliary patterning yarns into a base structure. Vertically positioned fabric supplied by a system of rollers is introduced to the embroidery mechanism. A frame holding needles threaded with patterning yarns faces the base fabric. Needles which are selectively activated penetrate the base fabric structure. The path of the needle frame dictates the orientation of the patterning yarn (Figure 7). This system can provide off-axis fiber orientation.

Lappet weaving and Schiffli embroidery were systems built for the manufacture of apparel fabric. Textile Technologies, Inc.'s investigation into the technology of these textile systems, sees the potential for composite application. Mechanisms controlling off-axis auxiliary yarns may be modified to accommodate high modulus yarns into the ground structural systems.

<u>Lappet Weaving</u>

<u>Advantages</u>

- Off-Axis Fiber Orientation

<u>Disadvantages</u>

- Machine Availability

It can be noted that Lappet Weaving has not yet been employed to weave high modulus fibers in 3-D preforms. However, technology research suggests the possibility of three-dimensional preforms with viable machine modifications.

<u>Schiffli</u>

<u>Advantage</u>

- Off-Axis Fiber Orientation

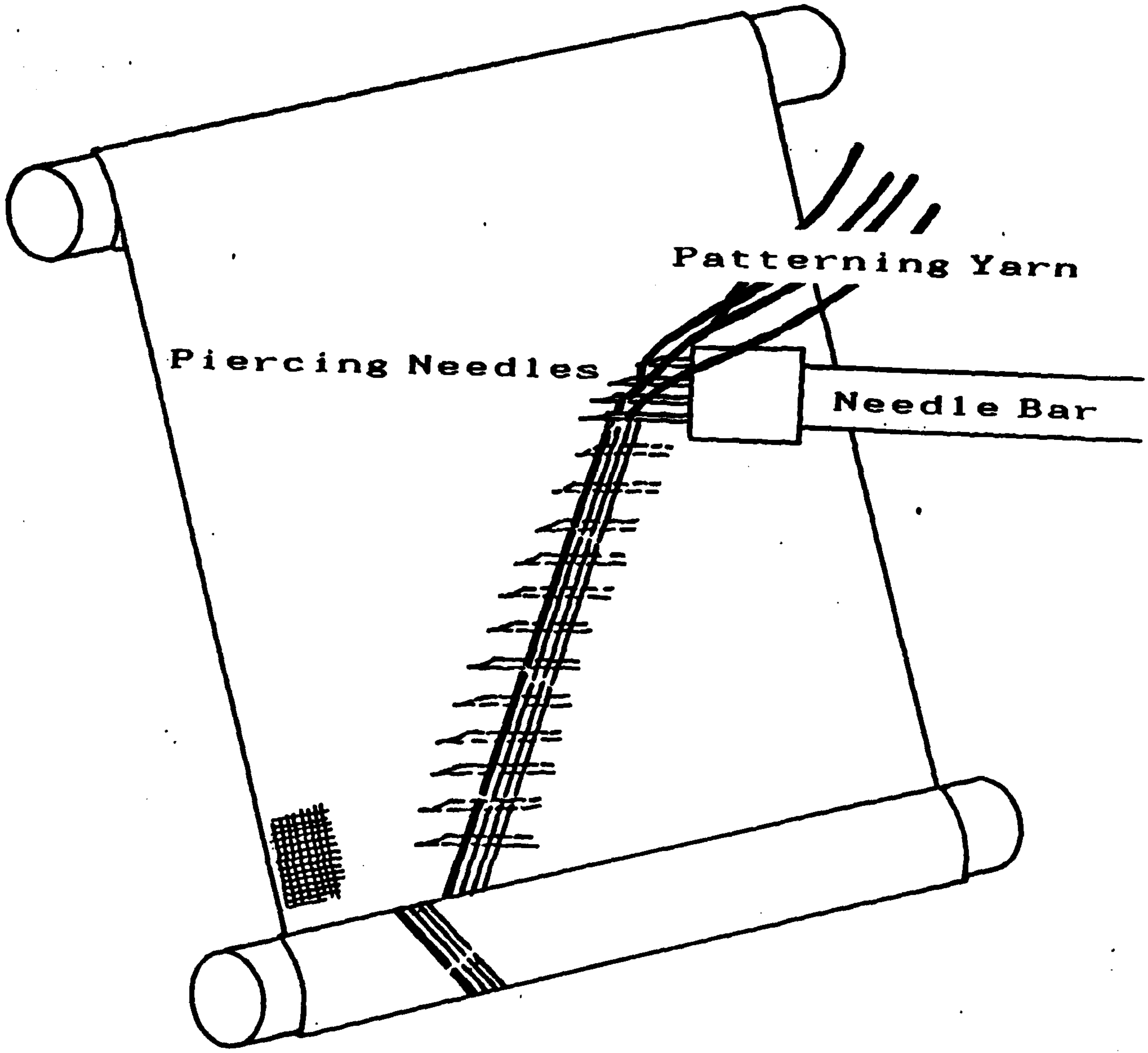


FIGURE 7 - EMBROIDERY FRAME

Disadvantage

. Highly Impaling Stitch Mechanism

Schiffli Embroidery systems have not been employed to stitch high modulus fibers into 3-D preforms. However, the mechanism associated with full scale embroidery production machines may provide a critical technology for "angular" weaving.

C. MULTI-DIRECTIONAL WEAVING TECHNIQUES

Multi-directional weaving technology provides a mechanism to produce structurally tailored composites. These processes have the ability to orient selected fiber types to accommodate the design loads of the final structural component. Multi-directional structures are fabricated by a variety of techniques including the weaving of dry fiber bundles, piercing of fabrics, assembly of prerigidized yarn structures, filament winding, and combinations of the aforementioned.

The simplest type of multidirectional structure is a three-dimensional orthogonal weave. Multiple fiber bundles are located within the structure on Cartesian coordinates in the x, y, and z directions (Figure 8). The yarn bundle size, spacing between adjacent yarn bundles, yarn packing efficiency, and the percent of yarn in each direction characterizes the 3-D fiber architecture.

The basic 3-D orthogonal weave design is modified to form a more isotropic woven structure. These structures have x-y in-plane fiber orientations reinforced with off-axis fibers plus z fibers through-the-thickness (0 degree/ +/- off-axis degree/ z). The 4-D structure is usually defined by 0 degree/ +/-60 degree in-plane fiber orientations and 5-D structure by 0 degree/ +/-45 degree/ 90 degree in-plane fiber orientations (Figure 9).

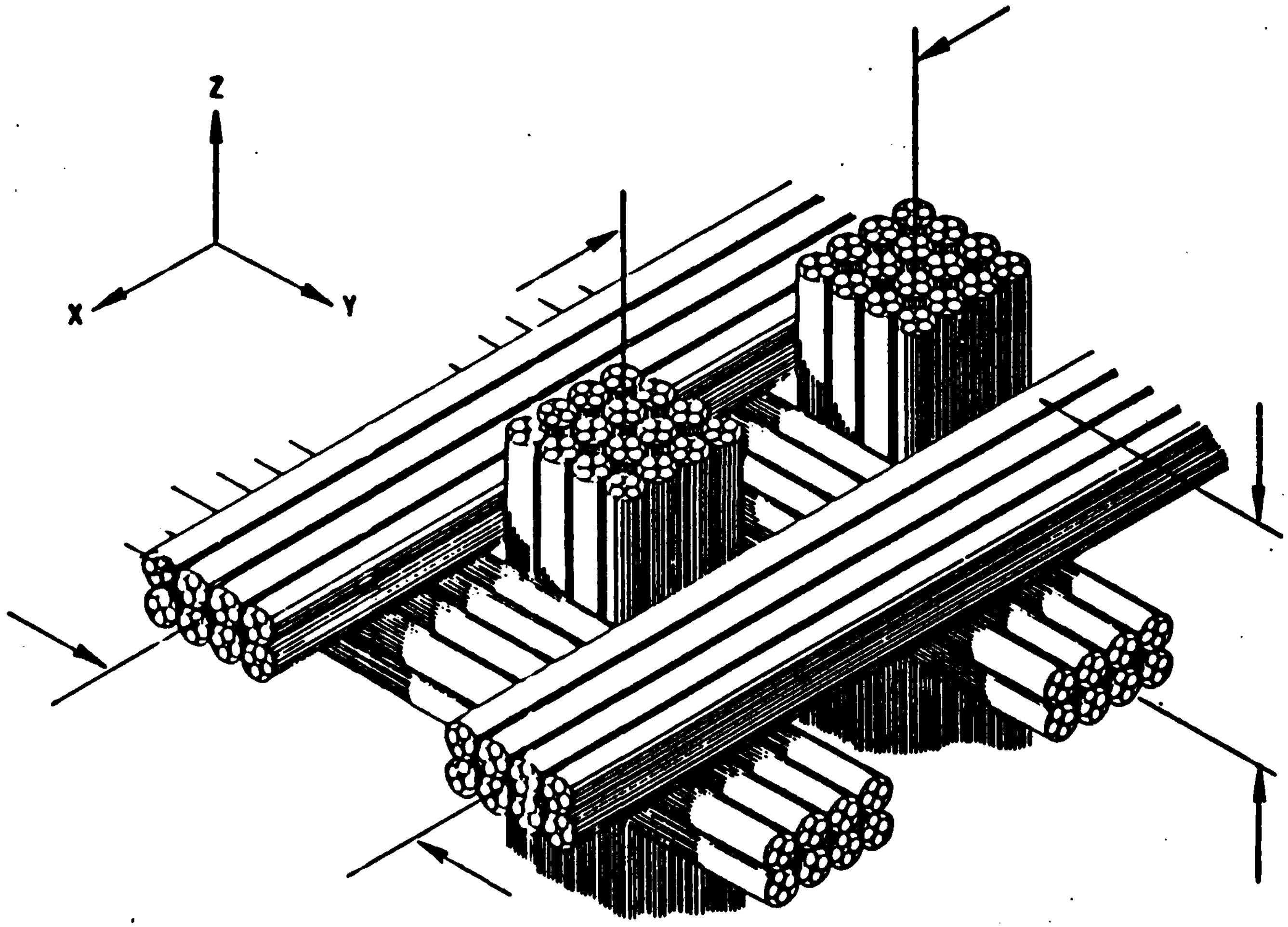


FIGURE 8-3-D ORTHOGONAL WEAVE

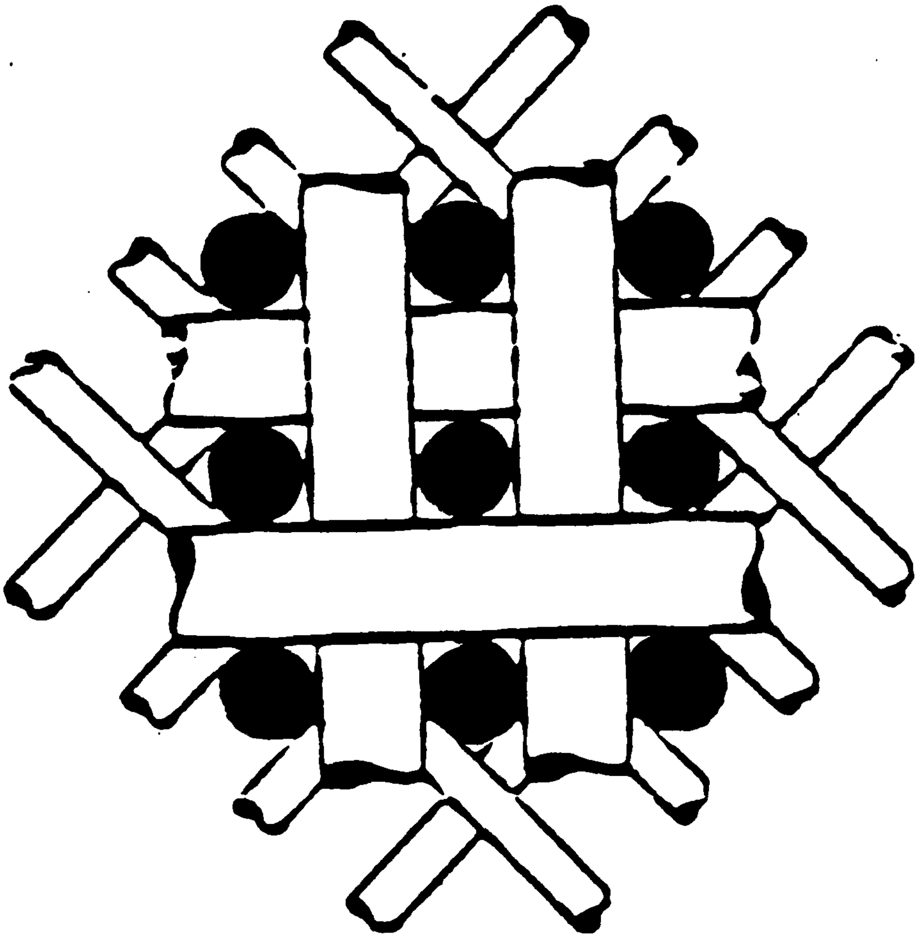


FIGURE 9 - 5-D CONSTRUCTION

Diagonal yarns are introduced into the preform as reinforcement to increase mechanical properties between the planes. Fiber preforms can be produced with up to eleven directions of reinforcement. The fabrication techniques decrease in production feasibility with the addition of each dimension.

Details of the machinery and procedures employed to manufacture multidirectional structures are typically proprietary. Mr. Paul G. Rolincik, Director of Autoweave™ Applications at Avco Specialty Materials - Textron, was generous in proving literature on Autoweave™ - the 3-D Automated Weaving Technique. General information on other "generic" multidirectional constructions will be discussed briefly. The following systems are covered:

. 3-D Orthogonal Block Construction	FMI/Generic
. Pierced Fabric Structures	Generic
. Autoweave™	AVCO
. Through-The-Thickness Braiding	Atlantic Research Corp.

3-D ORTHOGONAL BLOCK CONSTRUCTION

Several techniques have been employed to fabricate dry woven preform structures. 3-D orthogonal block constructions lay alternate horizontal rows of straight fiber bundles in the x and y directions. These fiber bundles are not interlaced. A row of thin tubes separates each adjacent yarn within an x or y horizontal layer plane (Figure 10). The weaving process progresses as subsequent layers of x and y yarns define a given thickness and the thin tubes are replaced with z direction fiber bundles. This results in an integrated x-y-z fiber architecture.

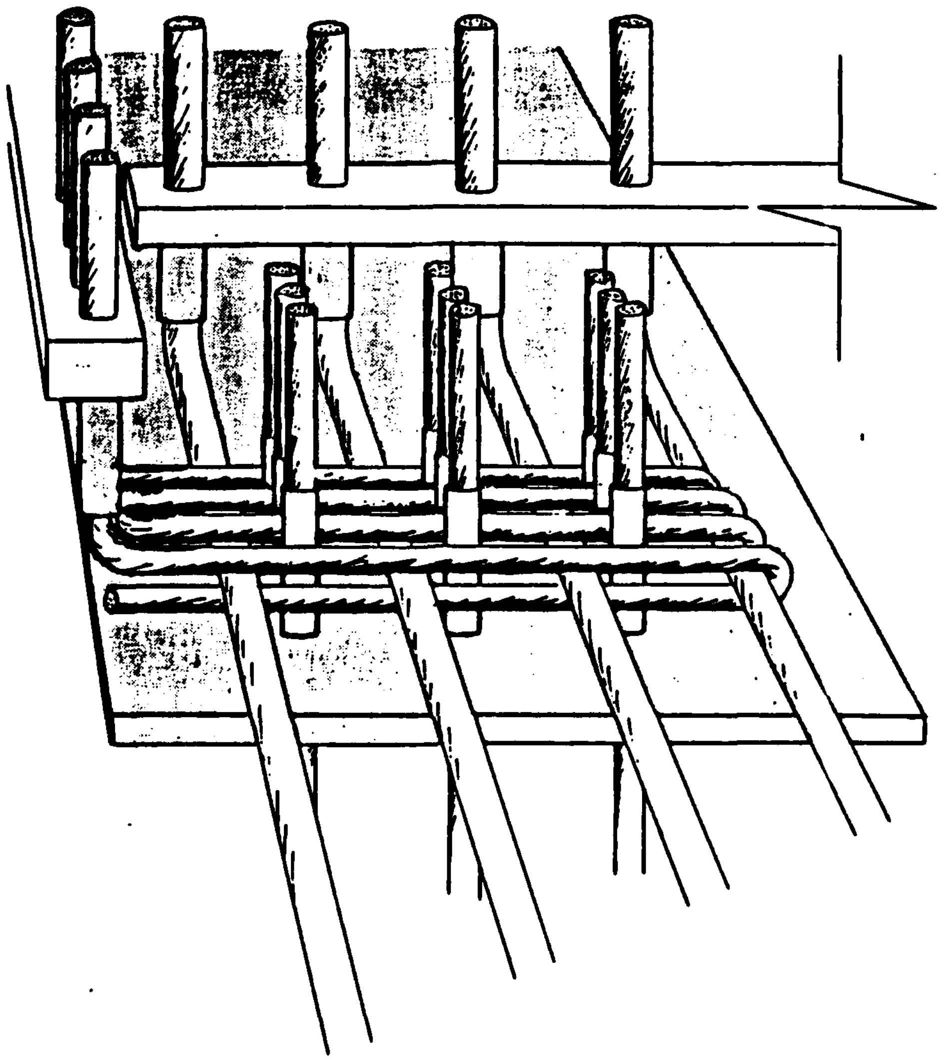


FIGURE 10 - 3-D ORTHOGONAL
BLOCK CONSTRUCTION

The 3-D orthogonal block construction produces various weave constructions. The type of yarn, size of yarn and distributions of yarns defines the construction. Fiber concentrations are controlled by varying the yarn size and the number of yarns per site in all three directions to yield desired volume fractions. The unautomated nature of the 3-D orthogonal block construction allows for modifications in the x and y direction yarns to yield off-axis fiber orientation. However, this is not a common procedure.

3-D Orthogonal Block Construction

Advantages

- 3-D, 4-D, 5-D
- Various Fiber Architectures
- High Modulus Fibers
- Moderate Fiber Volume Percentages
- Near Net-Shapes

Disadvantages

- Limited to Block Shape
- No Automation
- Extremely Low Production Rates
- Bias Angle Fiber Orientation Not Commom Procedure

PIERCED FABRIC STRUCTURES

The pierced fabric block construction is similar to the 3-D orthogonal woven block construction. Instead of separate systems of x and y yarns, 2-D woven fabrics are pierced over metal rods which represent the z-direction of the structure. The rods are subsequently replaced by dry or preimpregnated yarns to form the

three-dimensional structure (Figure 11).

This technique allows for a great deal of constructional variation. A multitude of 2-D woven fabrics can be constructed varying in fiber type, fabric sett (yarns per inch), and weave configuration. The x-y fabric plies can be rotated when positioned over the metal rods to yield +/-45 degree orientations. The pierced fabric block construction has the ability to yield a higher fiber volume and preform density than the 3-D orthogonal block construction. This system is unautomated resulting in production rates that are very low.

Pierced Fabric Structures

Advantages

- 3-D
- Various Weave Configurations
- High Modulus Fibers
- Moderate Fiber Volume Percentages
- Near-Net Shape Preforms
- +/-45 Degree Bias Angle Range

Disadvantages

- Each layer limited to the 2-D weave style
- Extremely Low Production Rates
- Limited Shape Range
- Not Automated

AUTOWEAVE™

Avco entered into a 15 year license agreement in 1984 with Brochier S.A. and the Commissariat a l'Energie Atomique (CEA) both

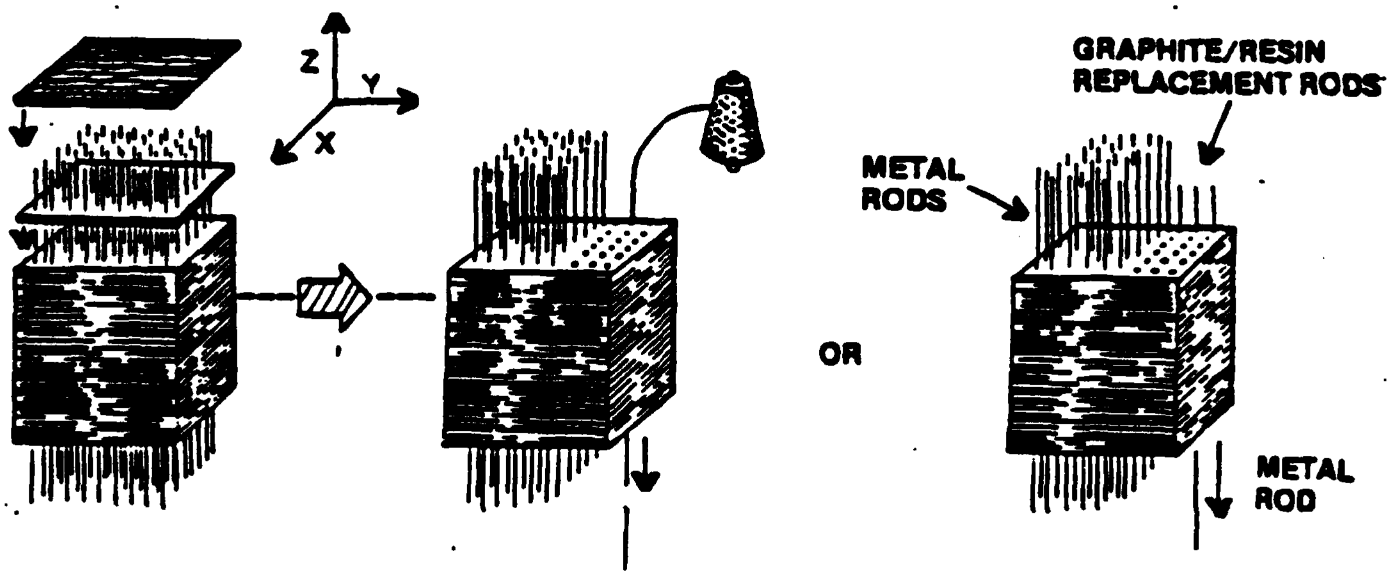


FIGURE 11 - PIERCED FABRIC STRUCTURE

of France for use of a 3-D automated weaving system. The Autoweave™ weaving system is part of a manufacturing technology program funded by the Air Force Wright Aeronautical Laboratories/Materials Laboratories, Ohio.

Two types of 3-D automated weaving machinery are employed by Avco, the BR900 and BR2000 system. The BR2000 installed in September 1986, is a scaled up version of the BR900 system working on the same principle. Near net-shape contoured preforms are fabricated on this equipment. A computer program is implemented to analyze input data describing the desired end product preform parameters such as fiber type, geometrical characteristics, fiber percentatges, density, etc. The resultant output defines the actual woven preform in terms of physical parameters and designates required amounts of material necessary to produce said preform.

The BR2000 system incorporates three different yarn systems: radial, circumferential and axial (Figure 12). The weaving process begins with the fabrication of a mandrel using rigid foam. The shape of the foam mandrel is defined by the preform. Radial rods, which are prepregged, precured yarns, are fabricated on a continuous spool, then automatically inserted, one per second, into the foam mandrel. The radial rods are arranged so as to form "corridors" through which the circumferential (1 revolution per second) and axial (15 inches per second) yarns are wound into alternate layers so as to mock weave (Figure 13).

A multitude of preforms can be fabricated on the BR2000 system. Fibers such as carbon, glass, Kevlar(R), quartz and silicon

AVCO AUTOWEAVE™ PREFORM CONSTRUCTION

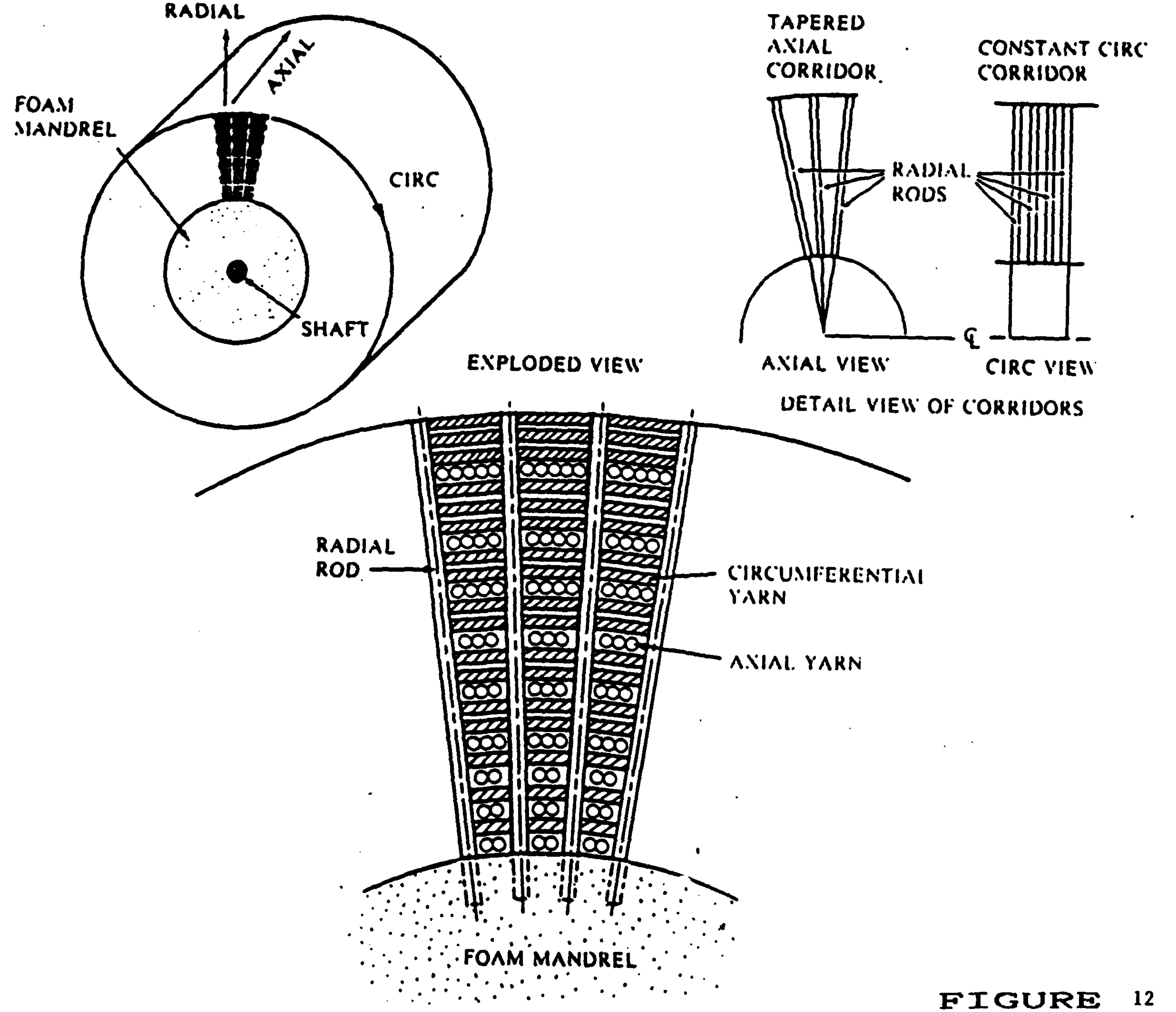


FIGURE 12

SCHEMATIC OF AUTOWEAVE™ 3-D MATERIAL

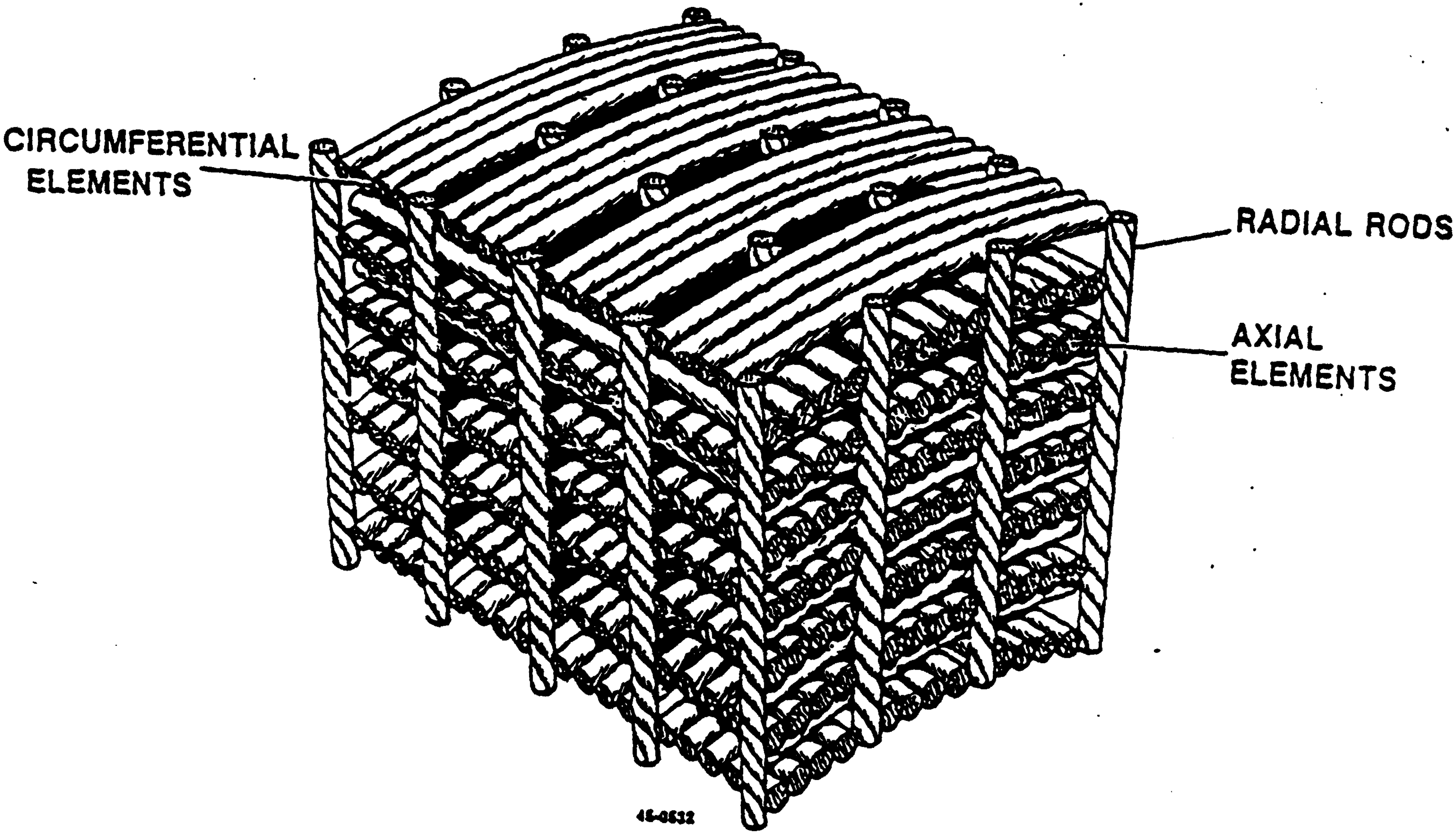


FIGURE 13

carbide ranging in size from 1K filaments to 12K can be processed. Parameters such as the size and shape of the foam mandrel, the size and type of the radial, circumferential, and axial yarns, the spacings of the yarns can all be altered to yield various woven preform structures ranging from balanced cylinders to internally and externally flanged contoured shapes. The BR2000 weaving system has a capability of weaving a 84 inch diameter, 60" long fiber preform varying in thickness from 0.25 inches to 8.0 inches with a fiber volume as high as 55 percent.

Production rates for a 40" diameter, 4-1/2 foot long, 5K graphite exit cone were provided by Avco. 300,000 radials implanted at one per second in the foam mandrel at spacings varying from 0.3 inches to 0.8 inches required 75 working hours. Eight hours were necessary to lay down one layer of axial and one layer of circumferential yarns to a 0.028 inch thickness. Total production time equalled six weeks itemized by one week for foam mandrel construction, two weeks for radial implantation and three weeks for axial and circumferential fabrication. Raw materials contribute 25% to the total final cost of preform with the remaining 75% due to production costs. A learning curve with a 33% cost reduction is expected to be eventually realized from the semi-automatic BR2 system.

Off-axis fiber orientation is not typically produced on the Autoweave™ system. However it is possible to obtain +/-45 degree yarn orientation during the winding process. The circumferential and axial yarns can be oriented at a +/-45 degree in conjunction with a 0/90 degree. The resultant preform would be five

dimensional in nature.

The largest contoured 3-D carbon exit cone fabricated to-date in the United States is a product of the BR2000 system. This preform does not have off-axis fiber orientation. The current applications of the Autoweave™ 3-D automated woven preforms are pre-production and production contracts for Air Force and Navy propulsion programs. The preforms are typically employed as integral throat entrance (ITE) components of rocket motors and as exit cones.

<u>Autoweave™</u>

<u>Advantages</u>

- Automated 3-D Weaving
- High Modulus Fibers
- Near-Net Shapes
- Up to 55% Fiber Volume

<u>Disadvantages</u>

- High Production Overhead Costs
- Low Production Rates
- Bias Angle Fiber Orientation Not Currently In Production

THROUGH-THE-THICKNESS MATRIX BRAIDING

Through-the-thickness matrix or three-dimensional braiding are a relatively new development. Braided composite materials have been under study in the aerospace industry since the late 1960's, such as "omniweave" by General Electric, and "scoudid" by Societe Europeennede Propulsion (SEP).

Through-the-thickness braiding is a technique for achieving three-dimensional seamless patterns by the continuous intertwining

of fibers. During the braiding operation, all of the fiber carriers move simultaneously. This process is distinguished from conventional braiding in that more than two plies are interconnected.

Cartesian through-the-thickness braiding uses an array of carriers capable of alternate rows and column position shifts as shown in Figure 14. Reversal of the direction of row and column motion during a complete shift cycle produces the intertwining of fibers.

Through-the-thickness braiding machines were first designed to fabricate 3-D rectangular panels. After successful demonstration of the panels, a circular braider was developed to provide conical and frusta shaped preforms. Recently, complex shapes have been developed by adjusting the length of travel (number of spaces shifted of each row and column as shown in Figure 15).

The mechanism is the same for each loom design. The row motion is accomplished by shifting ground tracks (e.g., rectangular or circular shaped) containing fiber carriers. Column motion consists of shifting the fiber carriers. Row and column motion is caused by mechanical or pneumatic actuators mounted about the perimeter of the apparatus. Thus, the motion of an interior fiber carrier is caused by the push from an adjacent carrier, or by shifting of the track beneath. Since every fiber undergoes similar motion, all fibers become entwined in a balanced array.

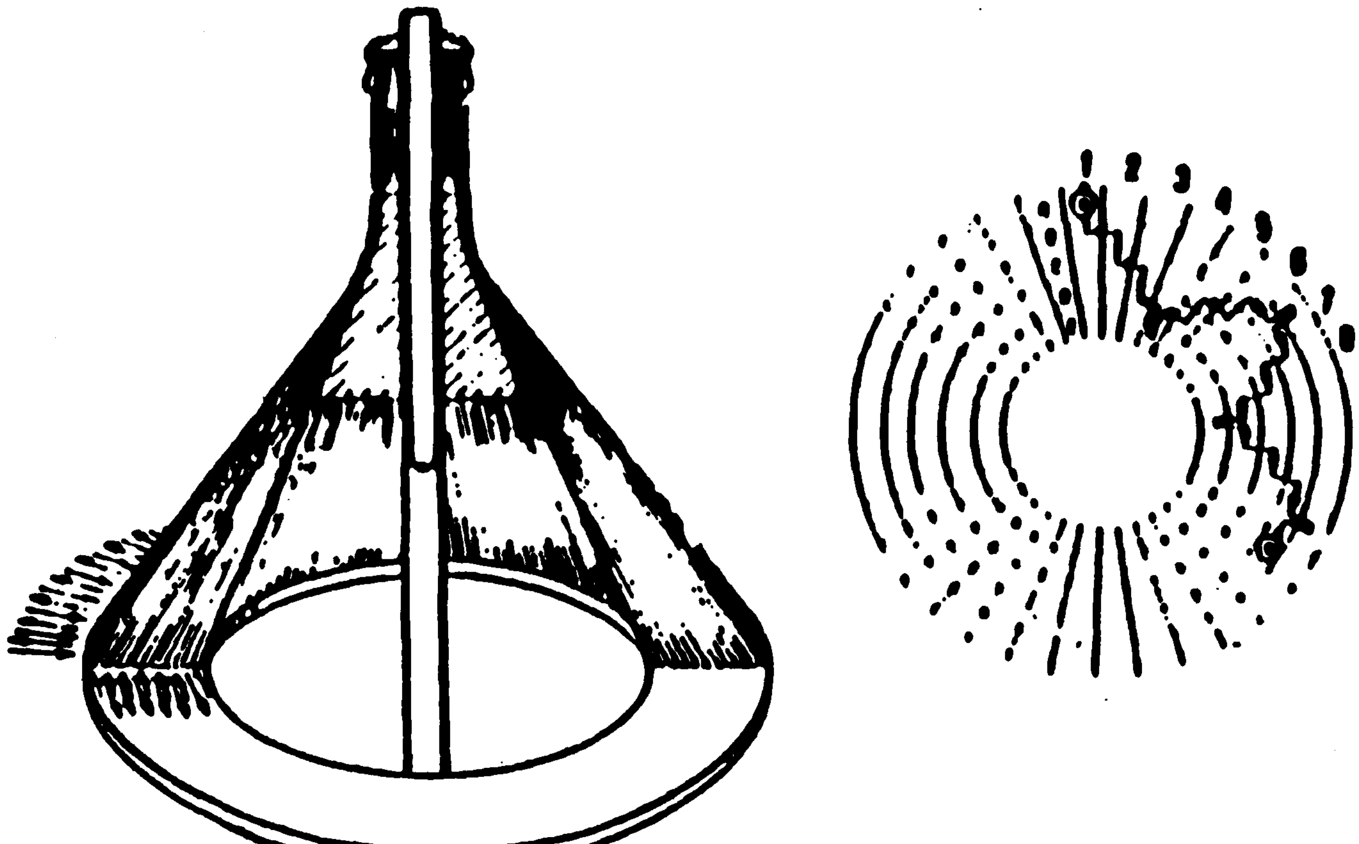


FIGURE 14 - THROUGH-THE-THICKNESS
CYLINDRICAL BRAIDING

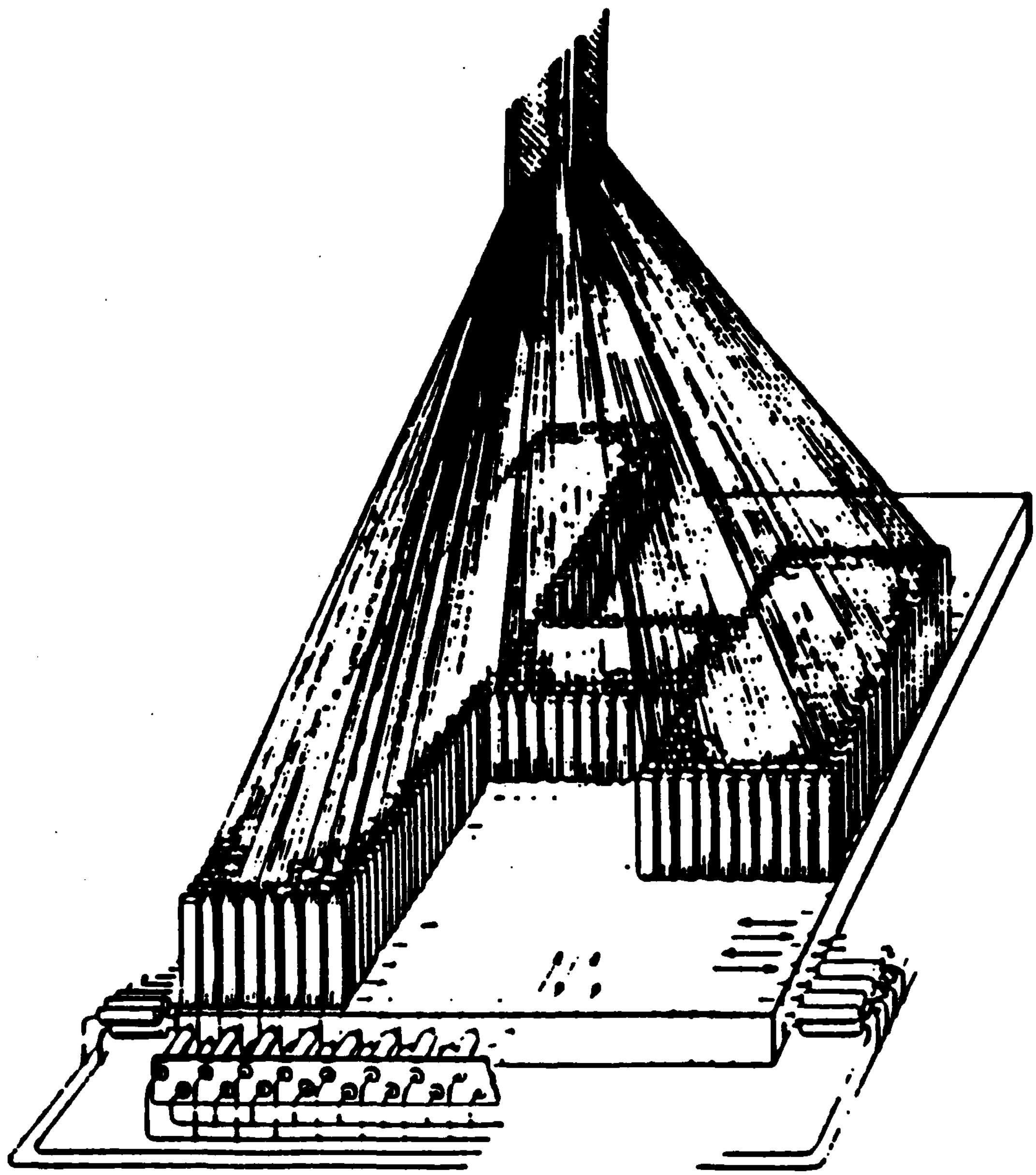


FIGURE 15 - THROUGH-THE-THICKNESS COMPLEX SHAPE BRAIDING

Two pneumatically activated through-the-thickness braiding machines include a 2016 fiber end carrier circular braider and a 12,222 fiber end carrier cartesian braider. These braiders were designed and fabricated at Atlantic Research Corporation.

As in two-dimensional braided structures, every braid pattern consists of a repeating unit termed a plait. The plait geometry is formed by the axis of two adjacent yarns, each pair moving in opposite directions. A braid can be distorted to a variety of extended or contracted positions with the plait spacing and cross-over angle changing in the process. When all yarns are lying side-by-side, the yarns are said to be jammed and pattern is closed. The yarn orientation is a function of the fiber width. In the case of tubular, the braid will tighten on a mandrel in a naturally jammed condition.

Nomenclaure for the braid geometries are directly related to the row and column motion. For example, a "2 x 1" braid designates that the rows are moved two positions and the columns, one position. Common braid geometries include 1 x 1; 2 x 2; 2 x 1; 3 x 1 and 1 x 1 (1/2) fixed. Column motion can be fixed so that specified yarns do not interwine, but allow the row carriers to form braid angles around them. This is very similar to warp insertion of two-dimensional braids. The fiber angle orientation is a function of the braid geometry which is directly related to the materials mechanical properties.

Unautomated through-the-thickness braiding can only produce parts as large as the machine permits. The part size would typically be one sixth of the machine size. This discontinuous

process uses a predetermined fiber length (specified by the machine height) which dictates the resultant part length. The combing operation which determines the density of the braid is not mechanically controlled. Through-the-thickness braiding has not seen significant technological advancements within the last decade to be considered a candidate for mass produced composite reinforcements.

Through-The-Thickness Braiding

Advantages

- Various Fiber Architectures
- Moderate Fiber Volume Percentages
- Near-Net Shapes

Disadvantages

- No Automation
- Extremely Low Production Rates
- Limited Part Size

D. MULTILAYER, MULTIDIRECTIONAL WARP KNITS

Multilayer, multidirectional warp knits (MMWK) provide fiber reinforcement in 0 degree, 90 degree and various bias angles. Produced in a single step process (double bias matt [DBM] produced by Knytex is a multi-step process), the MMWK fabrics are similar to the traditional ply lay-up preforms. The fiber architecture is illustrated by a system of weft (0 degree), warp (90 degree), and bias (+/-0) yarns stitched through-the-thickness with a chain or tricot warp knit stitch. A variety of MMWK fabrics exist, wherein the linearity of the bias yarns, the number of axes, the stitch geometry, and the stitching mechanism defines each process.

The following systems provide the state-of-the-art multilayer, multidirectional warp knit technology available in the textile industry today. The production technology is cited in part from a technology comparison submitted to Textile Technologies, Inc. (TTI) by Jeff Bruner, President of the Quantum Group, Inc.

. Multi-Axial Span Systems (M.A.S.S.)	Hi-Tech
. Multiaxial Malimo Warp Knit	Chima
. Multi-Axial Magazine Weft Insertion System	Mayer
. Multiaxial Warp Knit (MWK)	Liba
. Raschel Weft Insertion Warp Knit (WIWK)	J. B. Martin
. Double Bias (DB) - Double Bias Matt (DBM)	Knytex

MULTI-AXIAL SPAN SYSTEM (M.A.S.S)

The Multi-Axial Span System (M.A.S.S.) known by its trade name as SPANPLY was developed by Hi-Tech. A M.A.S.S fabric consists of multiple plies of parallel yarns (Figure 16). The angle of the yarns in each ply is predetermined. The plies are held in position by vertical (Z-axis) stitching yarns which penetrate the full thickness of the ply lay-up in the third axis.

M.A.S.S fabrics have successfully been produced from fiberglass, carbon, aramid, polyester, nylon, rayon and hybrid fibers. A wide range of yarn sizes can be used. Fabric widths are produced from narrow ribbons to 100 inches. The most common widths are 25 inches and 100 inches and it is generally not practical to change the machine knitting width due to excessive, machine downtime. The number of plies can vary from 1 to 6, but up to 10 plies have been fabricated. Angular ply orientation

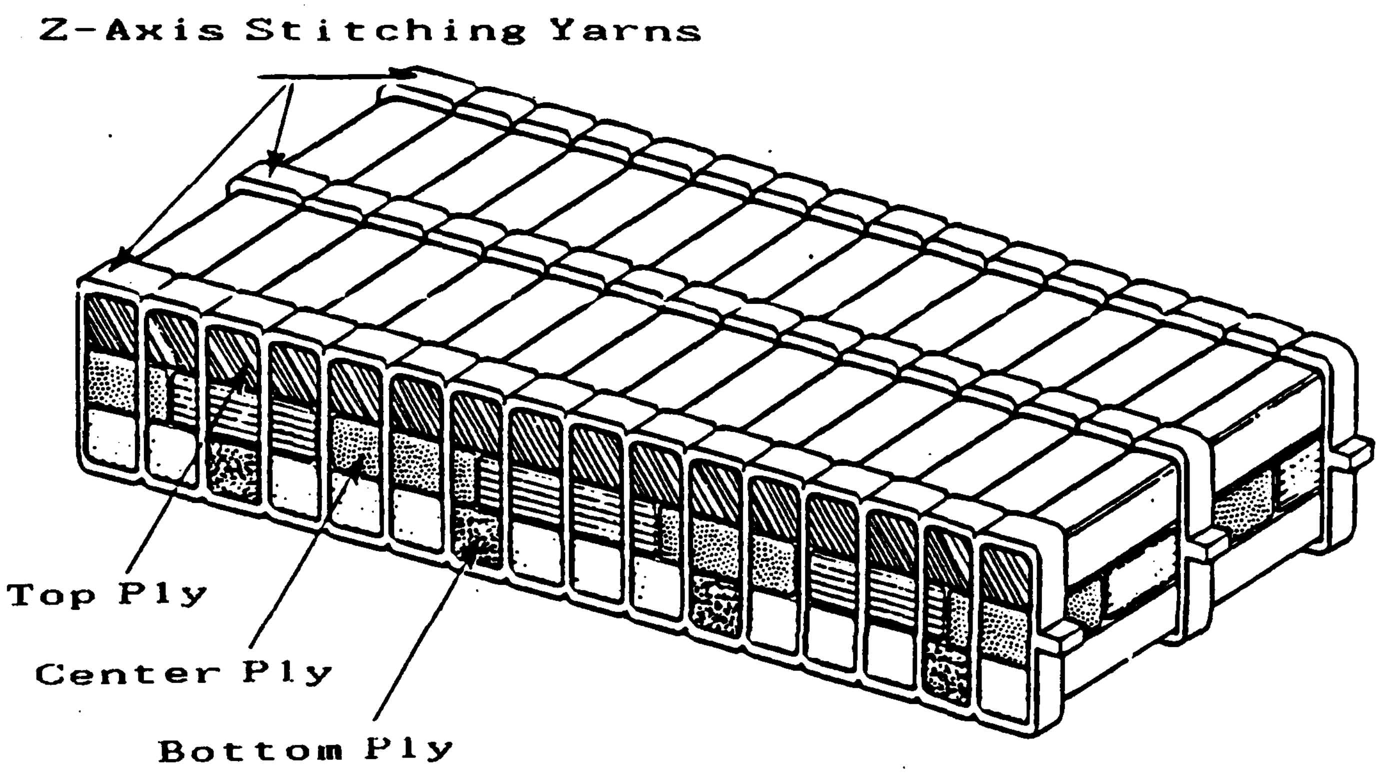


FIGURE 16 - MULTI - AXIAL SPAN SYSTEM

typically ranges from 30 degrees to 60 degrees in a linear or non-linear (zig-zag) fashion (Figure 17). Small angles to either side of 0 degrees are possible, but impractical, and angles greater than 45 degrees are currently in production. A maximum of 72 yarns can be packed into one inch; however, this is proportional to the yarn size.

The vertical stitch yarn may be any fiber with sufficient strength and flexibility. This so called Z-axis yarn is introduced into the plies of yarns with tricot, chain or lock stitch mechanisms (Figure 18). The degree of impalement (degradation caused by piercing a fiber bundle) is low. Stitch width spacing is typically 6 or 12 per inch and stitch length can be varied from 4 to 50 stitches per inch.

M.A.S.S. machines run at an efficiency of 75 to 90 percent at speeds up to 800 courses per minute. A typical hourly production rate of 70 yards per hour of a two ply +/-45 degree fabric with 12 yarns per inch in each ply. The production cost equates to 40% of the total fabric cost. This machine, exclusively built for Hi-Tech, cost between $150K to $200K.

The Spanply fabrics are being utilized in ballistic composite applications and as reinforcements for plastic construction applications. The fabrics characteristically have a flat, smooth surface with the potential for very high cover. Resin rich areas are not typical because of the ability to densely pack yarns into this system. High fiber volume percentages can be achieved. The M.A.S.S system is limited to the production of two-dimensional fabrics with a low range of thickness, typically less than 0.085

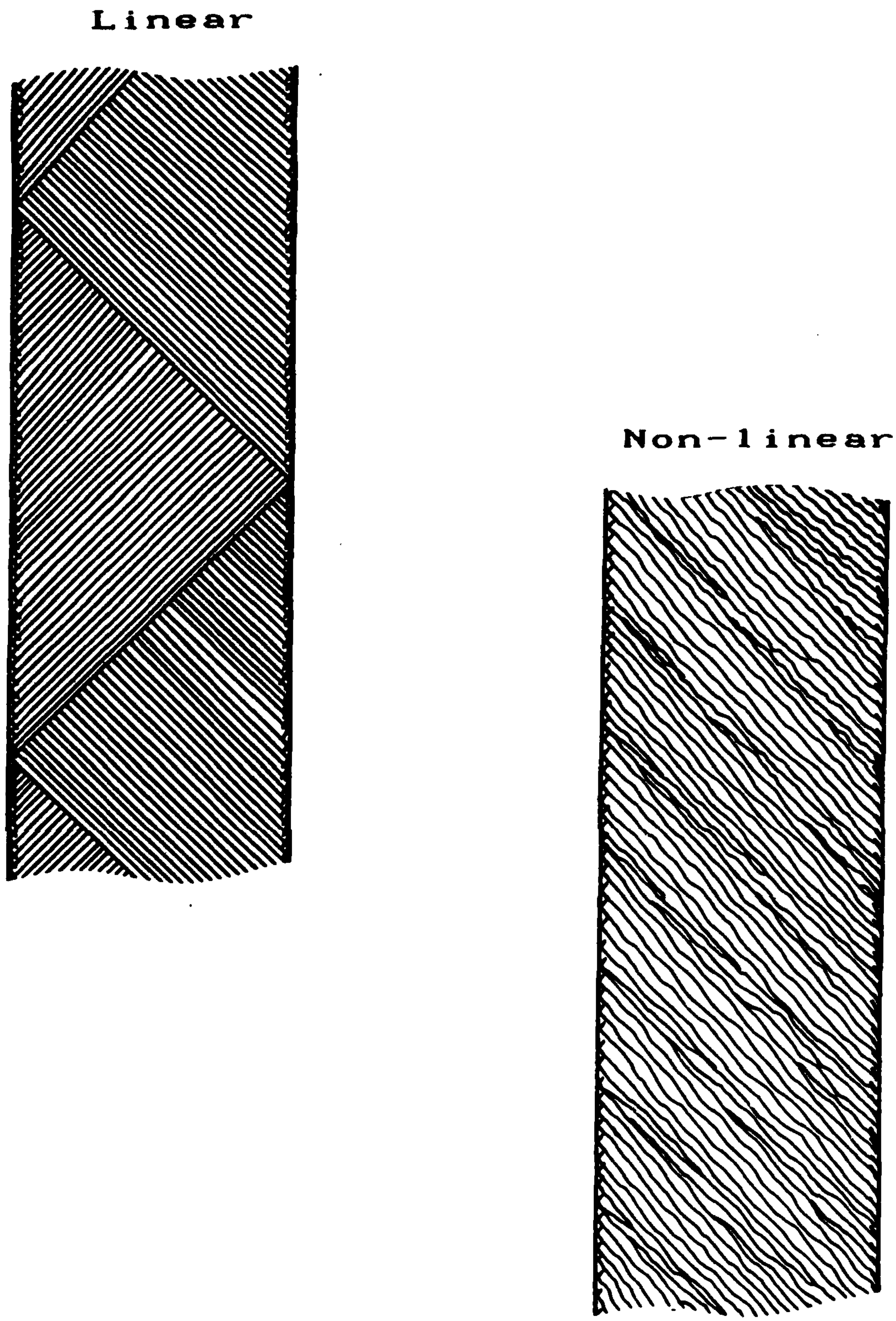
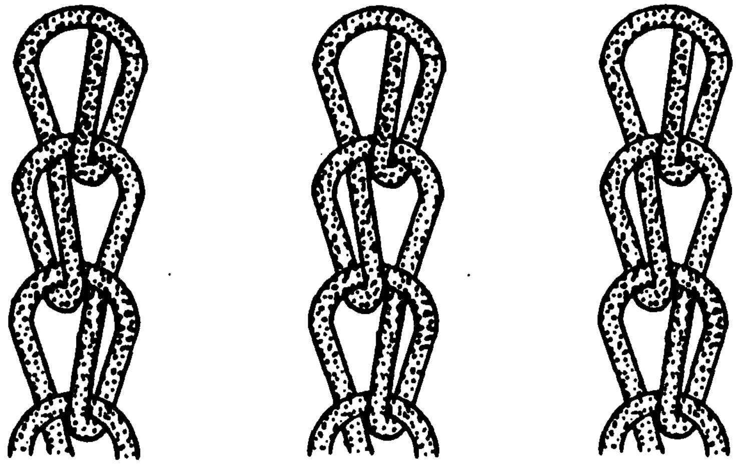
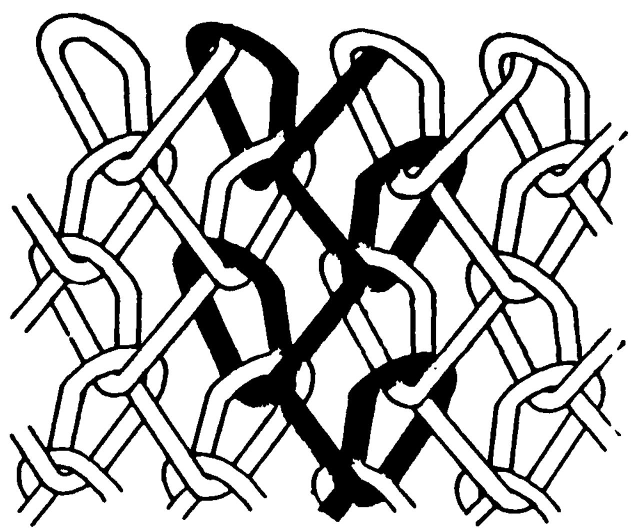


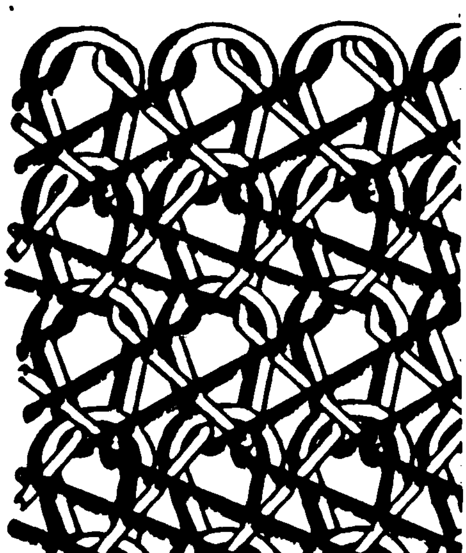
FIGURE 17 - LINEAR or NON-LINEAR YARN PLACEMENT



Chain Stitch

Tricot Stitch





Lock Stitch

FIGURE 18 - STITCH MECHANISMS

inches.

Multi-Axial Span System

Advantages

- Six Yarn Layers
- Bias Angle Range from 30 Degrees to 60 Degrees
- Up to 72 Yarns/Inch/Layer
- High Modulus Fibers in Yarn Layers
- Knitting Widths From Narrow Tapes to 72 Inches
- 70 Yards Per Hour Produciton Per Machine
- Fully Automated
- Resin Rich Areas Not Likely
- Fiber Volumes Up To 50%

Disadvantages

- Small Bias Angles Not Efficient
- Z-Axis Cannot Stitch With Carbon Fibers
- Lengthy Adjustments to Change Machine Knitting Width Between Production Runs Only
- Angle Change, Ply Orientation, and Width Change Are Not Automated
- Less Than 1/4 Inch Fabric Thickness
- Moderate to High Produciton Costs Per Yard
- No 3-D
- No Near-Net Shapes

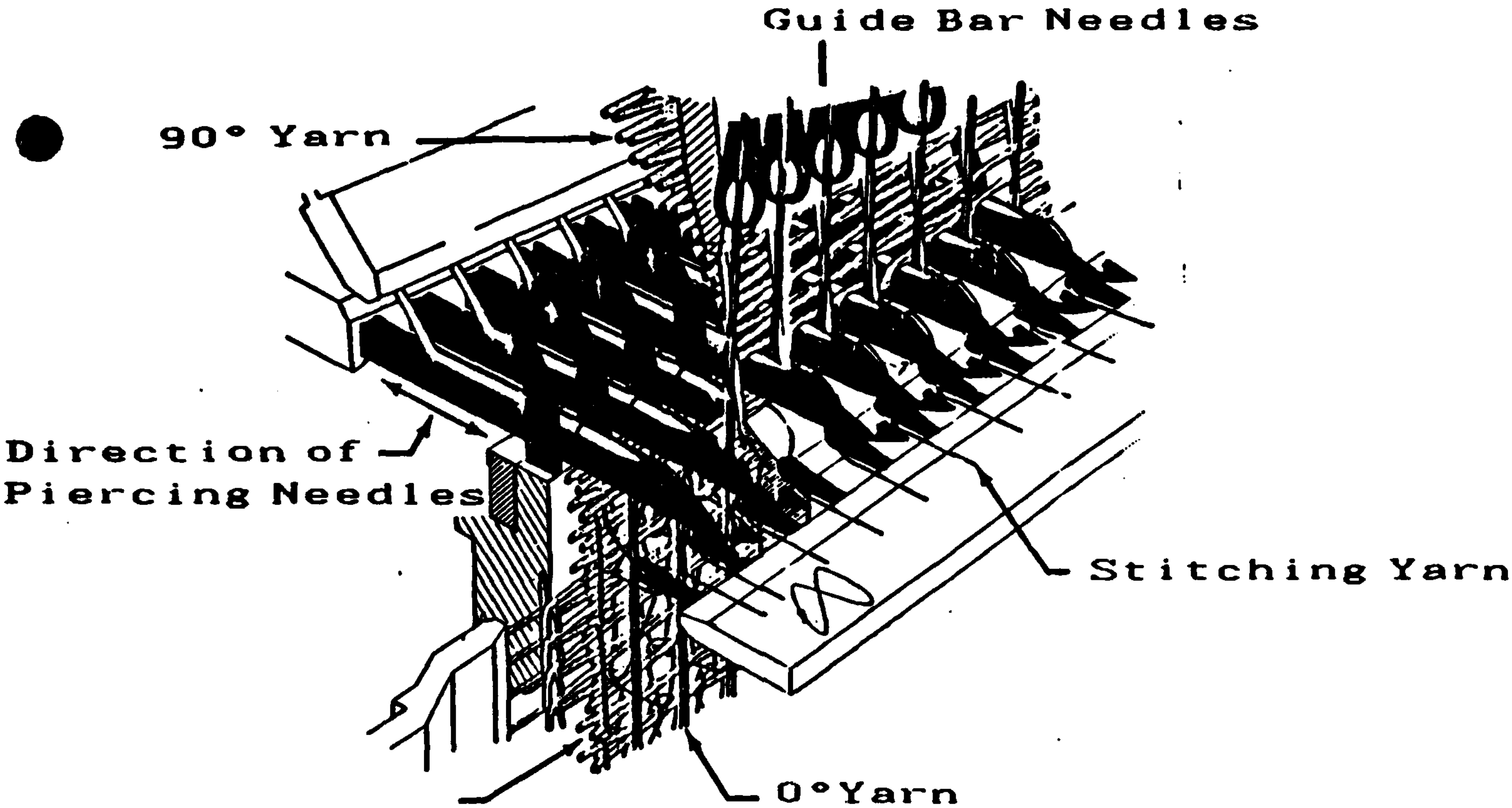
MULTIAXIAL MALIMO WARP KNIT

In 1986, Chima Inc. worked with Bean Fiber Glass to produce a machine capable of inserting yarns at a plus 45 or minus 45 degree angle. The technology is proprietary to Chima and Bean Fiber

Glass. However, the system developed uses the Malimo technique as its base technology. Malimo is a sewing-knitting machine. Stitching needles associated with sewing work together with guide bar needles characteristic of warp knitting. The stitching needles pierce through sheets of yarn to interact with threads supplied by guide bar needles, forming the Z-axis of the fabric, while interconnecting the layers of yarn (Figure 19).

The Multiaxial Malimo Warp Knitting machine has handled fiberglass rovings with yields ranging from 675 to 1800 yds/lb. Fabrics have been produced up to 60 inches in width. Width changes between production runs on one machine are not practical due to excessive machine down time. Therefore, a machine is typically set-up to run at a standard width all the time. This machine has the ability to stitch-bond sheets of yarns, base fabrics, films or fiber webs of up to 4 plies thick. Bias yarns can be placed in a non-linear (zig-zag) fashion at angles between 30 degrees and 60 degrees. Any changes from the current 45 degree bias yarn orientation would cause excessive machine down time. The number of bias yarns per inch per layer can be as high as twelve.

The piercing action of the stitching needles results in some yarn impalement. The piercing needles will actually pick up impaled fibers and then knit these fibers back into the structure. There is concern over the damage of impalement to the fibers by the piercing needles. This fabric is coarser than other multiaxials, but has a fairly smooth surface. The piercing capability of this system produces high cover fabrics with high



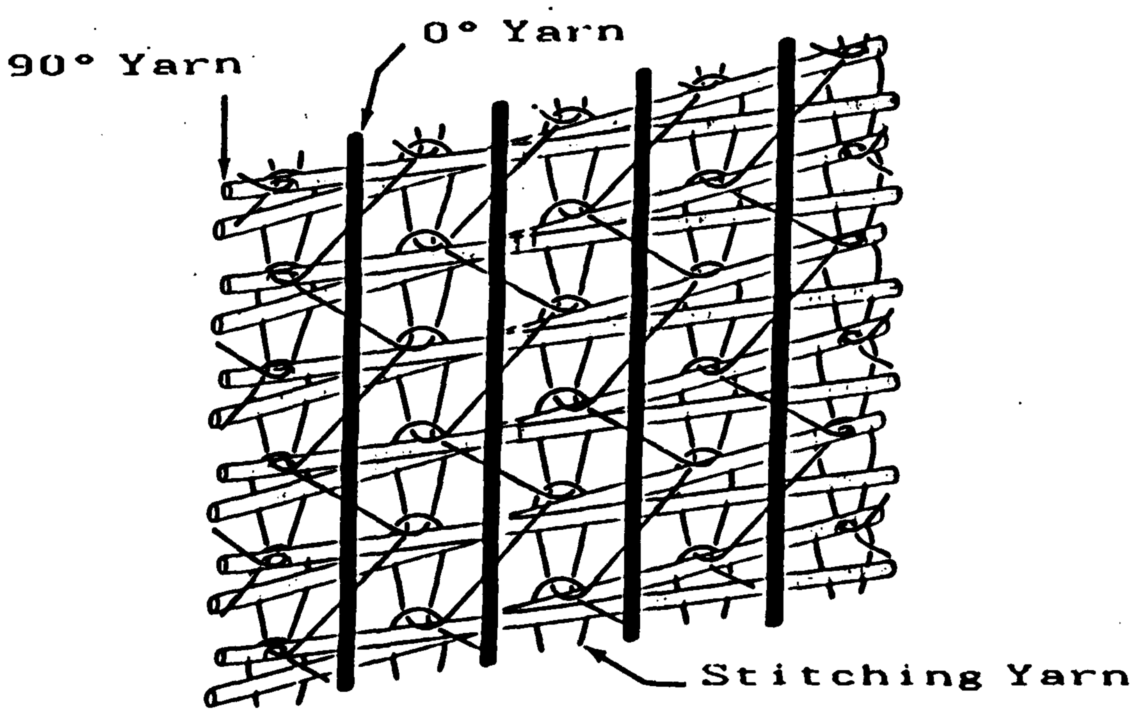


FIGURE 19 -MULTIAXIAL MALIMO WARP KNIT

fiber volumes and low incidence of resin rich areas. Fabric thicknesses are limited to a 1/4 inch with 2-D fiber architecture only. These fabrics are typically used to reinforce polyester resins in the marine industry.

Production rates on this specially designed Multiaxial Malimo Warp Knit machine can be up to 75 yards per hour at speeds of 800 courses per minute (a course is a row of stitches across a knitted fabric). Efficiency rates close to 90% translate into a low production overhead cost.

Multiaxial Malimo Warp Knit

Advantages

- Four Yarn Layers
- Bias Angle Range is 30 Degrees to 60 Degrees
- Up to 100 Inches Knitting Width
- 70 Yards Per Hour Production/Machine
- Low Production Cost Per Yard
- Fully Automated
- Low Incidence of Resin Rich Areas
- Fiber Volumes As High As 55%

Disadvantages

- Impaling Stitch Mechanism
- Lengthy Machine Adjustments To Change From Standard 45 Degree Bias Angle Setting
- 12 Yarns Per Inch Per Layer Limit
- Does Not Knit High Modulus Fibers
- Z-Axis Cannot Stitch With High Modulus Fibers
- Lengthy Adjustments To Change Machine Knitting Width

Between Production Runs Only

- Angle Change, Ply Orientation, & Width Changes Are Not Automated.
- Less Than 1/4 Inch Fabric Thickness
- No 3-D
- No Near-Net Shapes

MULTI-AXIAL MAGAZINE WEFT INSERTION SYSTEM

Karl Mayer introduced a multi-axial magazine weft insertion machine at the recent Techtextil Exhibition in Germany. The resulting fabric was knitted on a Raschel warp knitting machine. The RS 2 DS system incorporates five (5) yarn systems: Magazine Weft Insertion, Warp Threads, Two Diagonal Thread Arrangements, and Stitch Construction (Figure 20).

Aramid and fiberglass fibers ranging in yield from 5000 yds./lb. to 10,000 yds./lb. have been processed in each of the four load-bearing systems. Carbon and other high-modulus fibers have not been tested or sampled to-date on the RS 2 DS system. The Z-axis stitching yarn system has employed a 150 dtex polyester yarn and can accommodate yarns ranging in size from 70 dtex to 400 dtex. This process is distinctly different from other multiaxial warp knits in that it does not employ piercing needles in the Z-axis direction to stitch the layers of yarns together. Instead, round hook needles on guide bars either chain or tricot stitch through yarn spacings formed through the layers of yarn systems (Figure 20). This feature allows for non-impalement of the four load-bearing yarn systems with no filament damage. The

Magazine Weft Insertion
Two Diagonal Yarn Arrangements
Stitch Construction
Warp Yarns

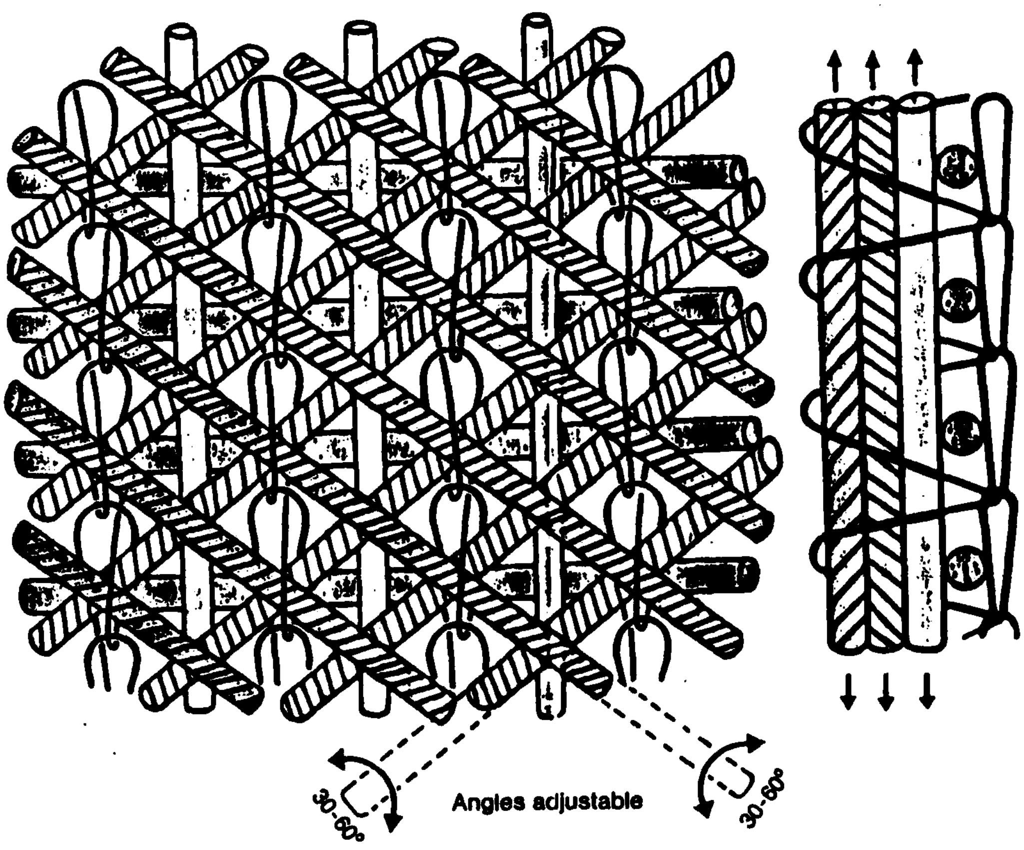
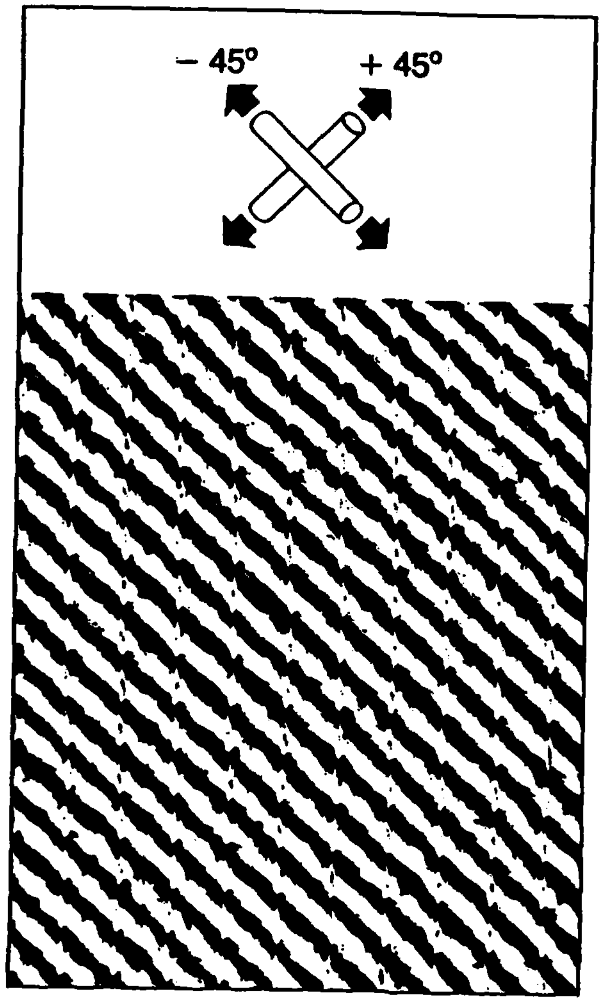


FIGURE 20 - MAYER RS 2 DS MULTI-AXIAL MAGAZINE WEFT INSERTION

openings through which the round hook needles pass can lead to resin rich areas.

The Mayer fabric can consist of two, three, or four yarn systems as well as a stitching yarn system (Figure 21). The yarn feed system allows for a very uniform distribution of yarns. The angle of insertion of the diagonal yarns is linear in fashion and can vary infinitely; however, a range between 30 degrees and 60 degrees is suggested. The linear placement of bias yarns produces a more isotropic fabric with balanced directional properties. Yarns cannot be densely packed into the structure and a range of 6 to 12 yarns per inch per layer is acknowledged. A low cover factor results from the scrim like structure. Yarns are moderately spaced, adjacent to one another in each layer, to allow clearance for the stitching needles. Although relatively thick fabrics (up to one inch) can be knitted on the Mayer RS 2 DS machine, only moderate fiber volumes can be achieved due to the stitching mechanism.

Fabric widths can be knitted varying in two inch increments from 40 inches to 60 inches. Relatively low production rates of 30 yards per hour can be achieved with machine speeds of 300 courses per minute. Machine costs exceeding $250,000 results in a high production overhead rate. Mayer cites the RS 2 DS fiber architecture as having potential in composite elements for air and space travel, automobile elements and construction elements for building sites and underground workings. The technology, which will not be available in the United States until mid-1987, is restricted to the production of two dimensional fiber



Two, Three, or Four
Yarn Systems

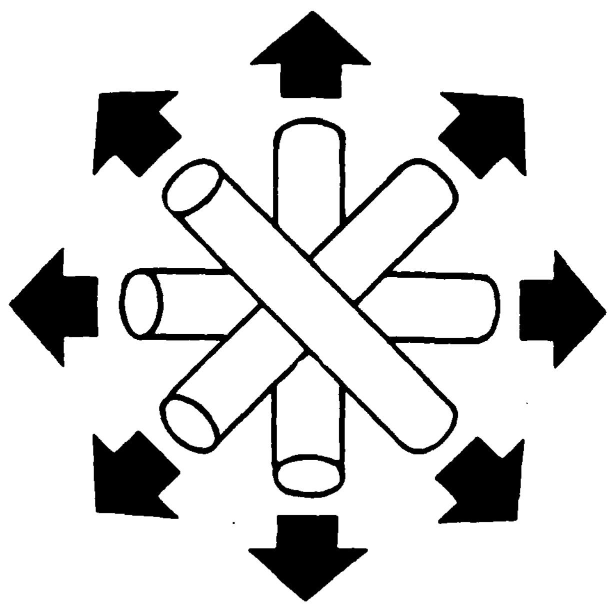


FIGURE 21-POSSIBLE YARN SYSTEMS

architecture.

Multi-Axial Magazine Weft Insertion System

Advantages

- Four Yarn Layers
- Bias Angle Range Infinite, 30 Degrees to 60 Degrees Is Most Efficient
- Non-Impaling Stitch Mechanism
- Up to One Inch Fabric Thickness
- Between 40 Inch and 60 Inch Knitting Width

Disadvantages

- High Modulus Fibers Cannot Be Knit
- Z-Axis Cannot Use High Modulus Fibers
- 12 Yarns/Inch/Layer Limit
- Moderate Fiber Volume Percentages
- 30 Yards/Hour Production/Machine
- Incidence of Resin Rich Areas
- Lengthy Adjustments to Change Machine Knitting Width Between Production Runs
- High Production Overhead Rate
- No 3-D
- No Near-Net Shapes

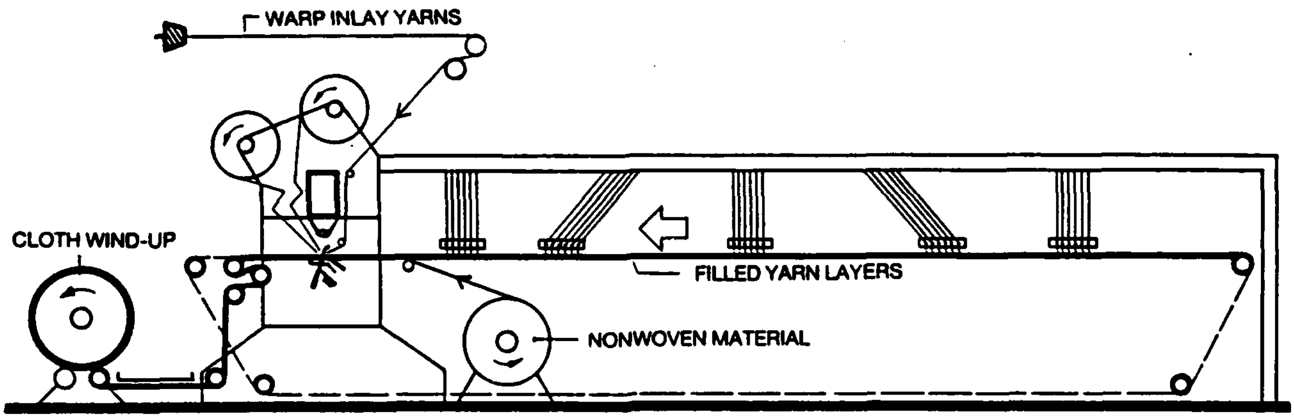
MULTIAXIAL WARP KNIT (MWK)

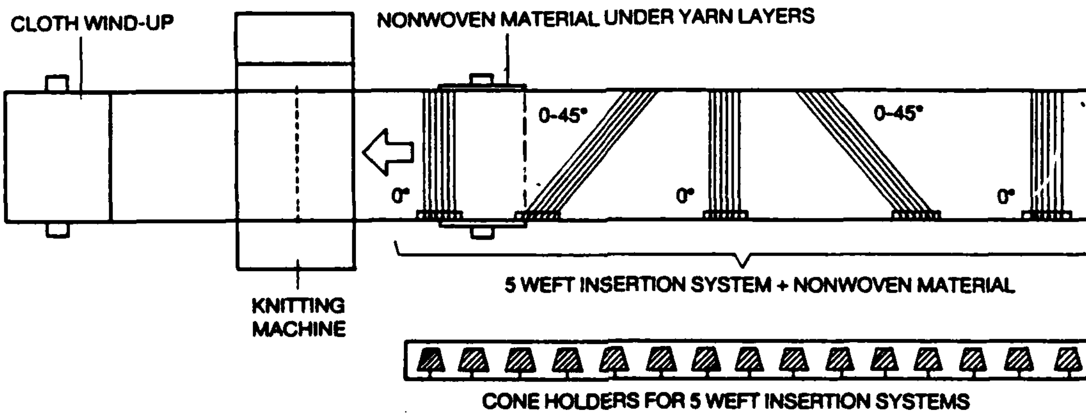
Responding to the need for multiaxial fiber orientation in fiber reinforced composites, Liba Company developed a multi-weft insertion warp knitting machine. The system is comprised of five (5) weft insertion systems, an auxiliary nonwoven material layer, and a Z-axis tricot stitching action. A yarn supplying device

located behind the knitting machine employs yarn carriers running on tracks to lay yarns at specified angles and to build a predetermined numbers of yarn layers (Figure 22). The laid yarn layers are run through the knitting machine and are penetrated with a tricot warp knitting stitch.

The yarn laying system has five (5) weft insertion systems. Three (3) systems work as parallel weft orienting yarns in the 0 degree and 90 degree positions. The remaining two (2) systems orient the diagonal weft threads in adjustable angles from 30 to 45 degrees (Figure 23). Actual fiber angle orientation between 0 degrees and 50 degrees can be achieved on this system. A 60 degree angle is possible by forfeiting the other diagonal system. The angle of insertion of the diagonal yarns can be in a linear or non-linear (zig-zag) fashion (Figure 17). The auxiliary nonwoven material layer on the bottom ply position can be substituted with a 0 degree yarn layer.

The Z-axis stitching mechanism is accomplished with a tricot warp knit stitch formed by piercing needles. As opposed to the chain stitch, the tricot stitch with its mechanism of jogging back and forth on adjacent needles creates a fabric. The piercing action of the needles, creating the tricot stitch, impales the fiber bundles as they penetrate the layers of yarns. The yarn layers can be laid in various desired densities, dependent upon the machine guage. The layering sequence can be changed quite readily. High modulus fiber tows ranging in yield from 2400 yds/lb to 20,000 yds/lb have been processed on the WIWK machine achieving up to 72 yarns per inch. Six layers of yarn can be





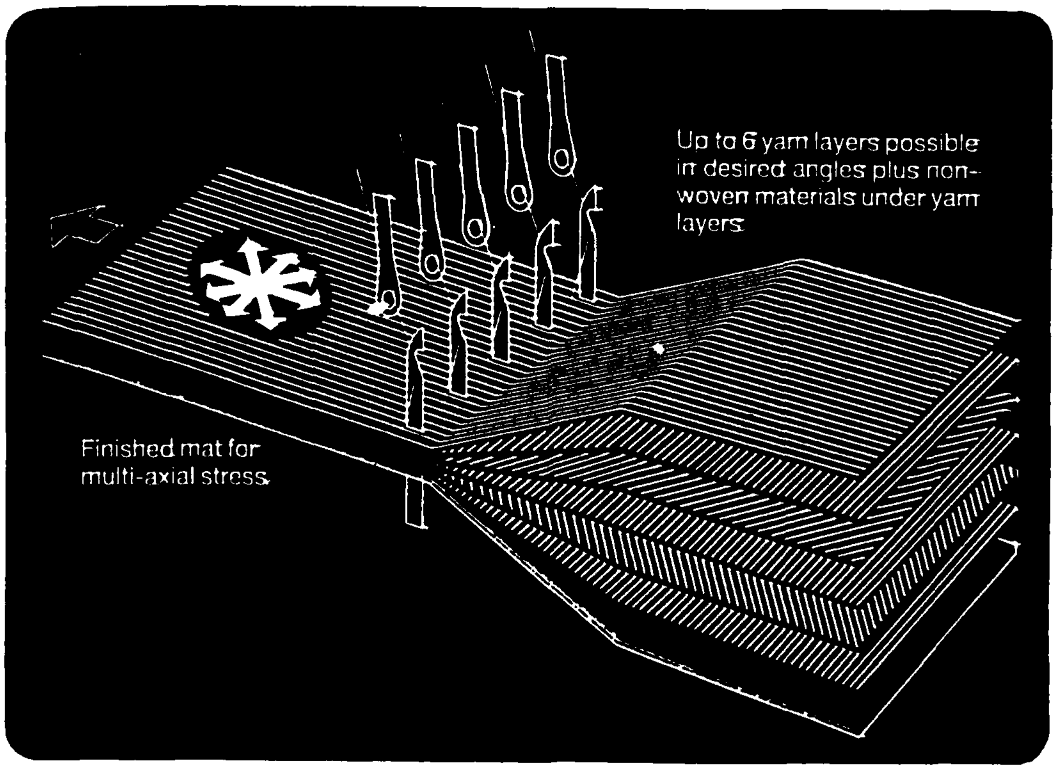
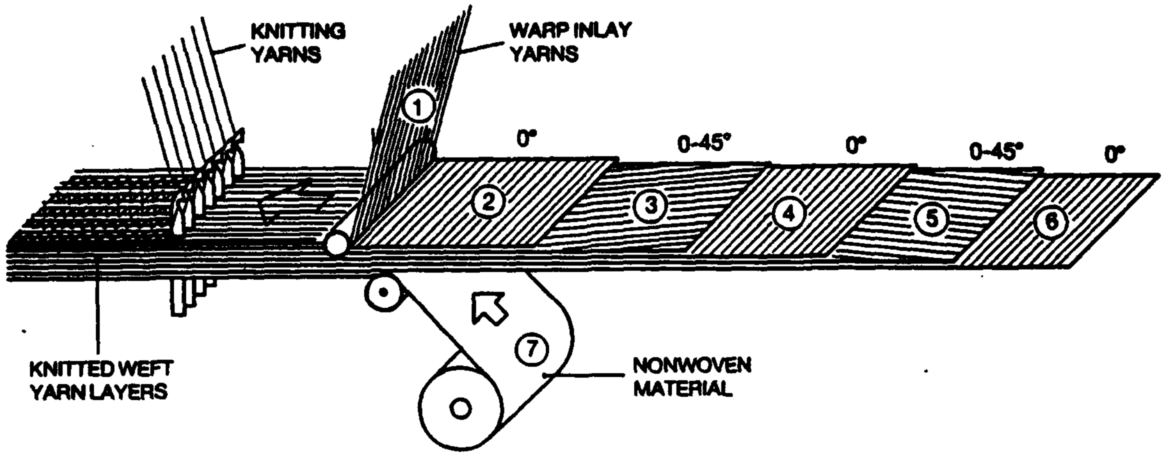


FIGURE 22-LIBA MULTI-AXIAL WARP KNITTING MACHINE



Number of layers	Possible yarn layers for LIBA multi-axial warp knitting machine with magazine weft insertion COPCENTRA HS 2-ST-MS5-VU				
1 layer	1x warp inlay	1x weft inlay	1x diagonal	1x diagonal	
2 layers	1x warp inlay 1x weft inlay	1x weft inlay 1x diagonal	1x warp inlay 1x diagonal	1x diagonal 1x diagonal	
3 layers	1x warp inlay 1x warp inlay 1x diagonal	1x weft inlay 1x diagonal 1x diagonal	1x warp inlay 1x diagonal 1x diagonal		In addition to each of the shown yarn layers, a nonwoven fabric can be fed under the fabric layers
4 layers	1x warp inlay 1x weft inlay 1x diagonal 1x diagonal	1x warp inlay 2x weft inlay 1x diagonal 1x diagonal	1x warp inlay 3x weft inlay 1x diagonal 1x diagonal		

FIGURE 23 - WEFT INSERTION SYSTEMS

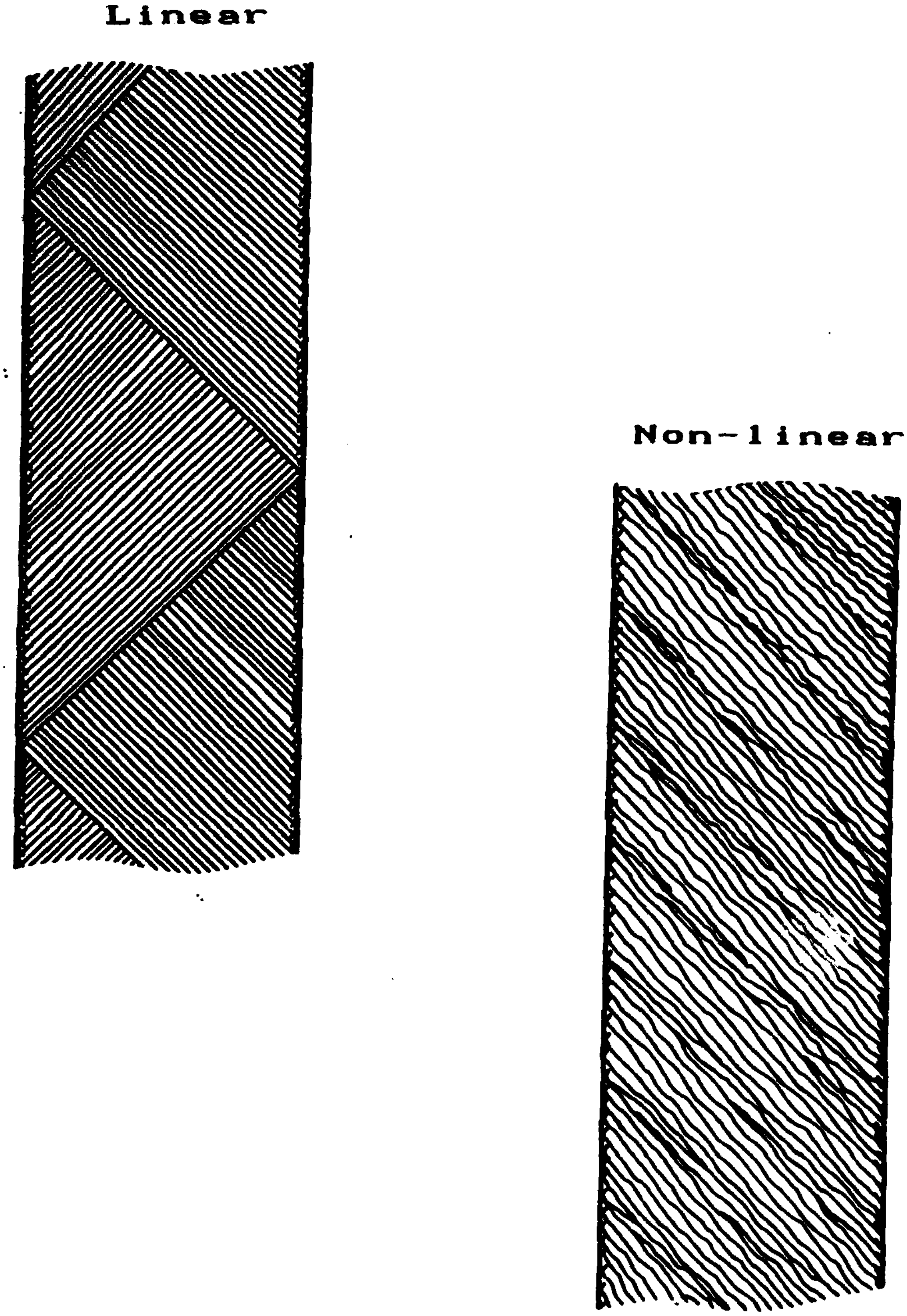


FIGURE 17 - LINEAR or NON-LINEAR YARN PLACEMENT

stitched together with the standard machine; however, with machine modifications fabrics with up to ten layers have been manufactured. Resulting fabric thicknesses are less than 1/4". High fiber volume structures can be achieved which result in fiber-to-resin volume ratios of 50:50 to 80:20. In these structures, resin rich areas are unlikely. MWK fabric widths can be varied as a function of the machine widths. The available machine widths are 25 inches, 50 inches, and 100 inches. It is generally not practical to change the knitting width between production runs. Machine knitting width modifications create excessive production down time. Currently, the Liba machine is only available in Germany. Production rates close to 700 rpm yield 70 yards of fabric per hour with high (75-90%) efficiency rates. The Liba machine has a $250,000 price tag. Production overhead rates are near 70% of total fabric costs. Materials have been processed for fiber reinforced composites used today in the aircraft and aerospace industry, in boat building, the automotive industry, and surface and underground engineering.

Multiaxial Warp Knit (MWK)

Advantages

- Six Yarn Layers
- Bias Angle Range Is 0 Degrees to 50 Degrees
- 72 Yarns Per Inch Per Layer Maximum
- High Modulus Fibers
- Machine Widths of 25 Inches, 50 Inches and 100 Inches
- 70 Yards Per Hour Production/Machine
- Fully Automated

- Low Incidence of Resin Rich Areas
- Fiber Volumes Up to 80%

<u>Disadvantages</u>

- Impaling Stitch Mechanism
- High Modulus Fibers Are Not Efficiently Run
- Z-Axis Cannot Stitch With High Modulus Fibers
- Lengthy Adjustments to Change Machine Knitting Width Between Production Runs Only
- Moderate to High Production Cost Per Yard
- Angle Change, Ply Orientation, and Width Changes Are Not Automated
- Less Than 1/4 Inch Fabric Thickness
- No 3-D
- No Near-Net Shapes

RASCHEL WEFT INSERTION WARP KNIT (WIWK)

J. B. Martin Company is investigating the use of a basic Raschel type Weft Insertion Warp Knit machine for development of multiaxial fiber preforms for composite application. The Raschel machine consists of a single needle bar working with a lay-in-bar to selectively lay-in off-axis yarns.

A Raschel machine is a warp knitting machine which uses a single set of vertically mounted latch needles. This single needle bar forms a chain stitch comprised of an underlap and overlap. The chain stitch is not a fabric in itself. The laid-in thread supplied by the lay-in bar is caught between the overlap and underlap of the chain stitch (Figure 24). The lay-in thread extends across as many adjacent needles as the swinging motion or

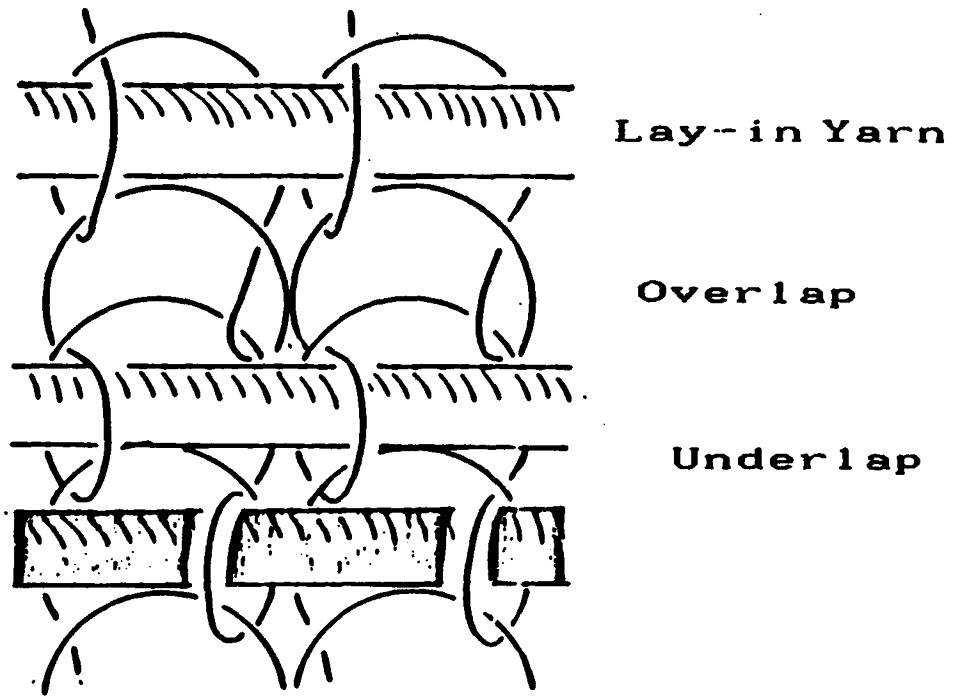


FIGURE 24 - RASCHEL WEFT INSERTION WARP KNIT

shogging of the lay-in bar will permit. The angle of the lay-in is determined by the lateral movement of the lay-in bar, the vertical chain stitch formation of the needle bar, and the resultant distortion that may occur in the chain stitch ground structure. It can be seen that this fabrication technique prohibits a continuous bias yarn insertion. The shagging of the lay-in bar allows a maximum two inch bias yarn length in a given direction before it reverses its swinging action. This shagging back and forth creates zig-zag yarn formations (Figure 25).

The fabric cover is affected by the number of needles per inch in the machine. Raschel weft insertion warp knit machines can be obtained with up to 16 needles per inch. A low cover results from the inability to pack yarns closely within the stitching mechanism. The lay-in motion allows for the insertion of very large diameter yarns into the fabric structure as well as high modulus yarns. The single needle bar forming the chain stitch is limited by the size of yarns that can be accommodated by the latch needles. Three to four layers of bias yarns are possible on the single needle bar machine; however, the addition of guide bars substantially increases the number of layers. Fabric thicknesses up to two inches have been fabricated. Low fiber volumes with resin rich areas are a result of the limited fabric cover. Machine speeds up to 500 courses per minute translate into hourly production rates of 50 yards working at 70-85% efficiency. Low overhead production rates can be realized with this system. Machine costs are relatively inexpensive at an average of $70,000.

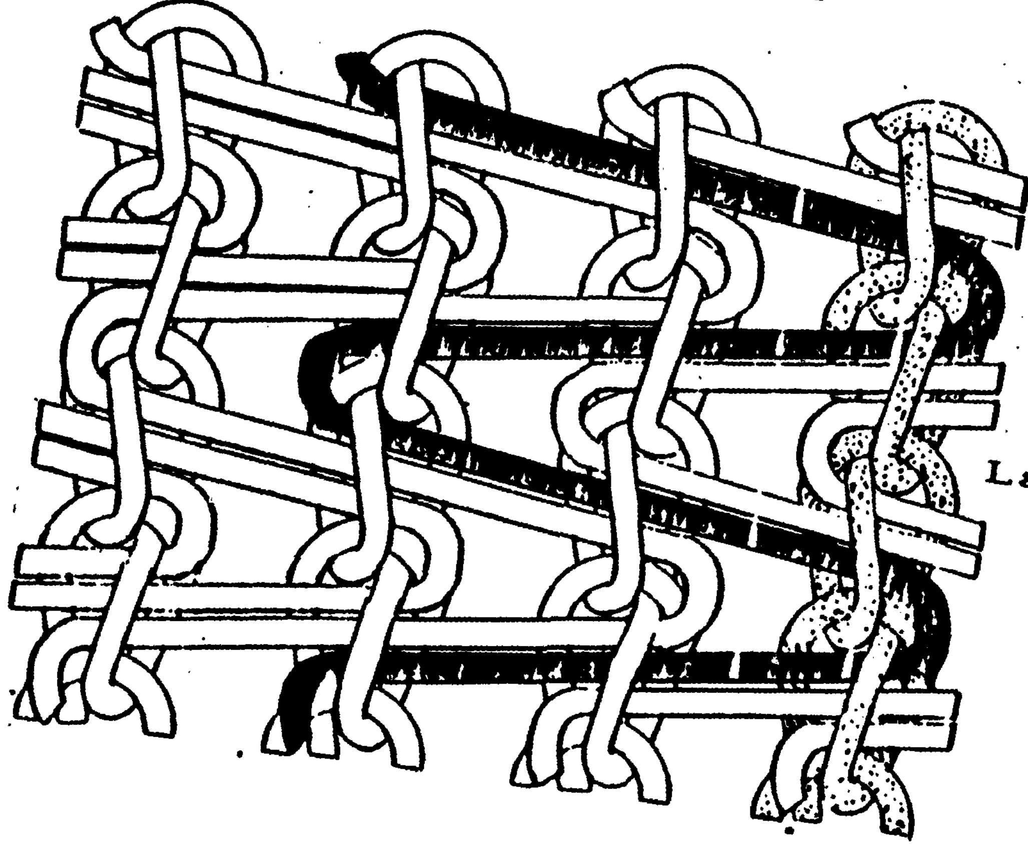


FIGURE 25 - RASCHEL LAY-IN
ZIG-ZAG YARN FORMATION

Three-dimensional structures such as I-Beams can be fabricated on the Double Needle Bar Raschel. The +/-45 degree oriented yarns layed into the structure by the guide bar are limited in continuous yarn length (less than two inches) by the shagging motion. The shagging motion will therefore limit the size of the fiber preform. Currently, this is the only multidirectional warp knit process that can achieve both off-axis fiber orientation and three-dimensional design capability.

Raschel Weft Insertion Warp Knit (WIWK)

Advantages

- Non-Impaling Stitch Mechanism
- Four Yarn Layers
- +/- 45 Degree Fiber Lay-In
- High Modulus Fiber Lay-In
- Up to 100 Inches Knitting Width
- 50 Yards/Hour Production/Machine
- Low to Moderate Production Cost Per Yard
- Fully Automated
- Less Than Two Inch Fabric Thickness
- 3-D
- I-Beam Preforms

Disadvantages

- Bias Angle Yarn Length Restricted to 2 Inch Zig-Zag
- 16 Yarns Per Inch Per Layer Limit
- High Modulus Yarns Cannot Be Knitted, But Are Lay-In
- Lengthy Adjustments to Change Machine Knitting Width Between Production Runs Only

- Width Changes Not Automated
- High Incidence of Resin Rich Areas
- Low Fiber Volume Percentages
- Bias Yarns Can Only Be Layed-In One Layer If a Multi-Layer Fabric is Being Knitted

DOUBLE BIAS (DB) - DOUBLE BIAS MATT (DBM)

Knytex, Inc., a subsidary of Xerkon, manufactures the Double Bias (DB) and Double Bias Matt (DBM). A DB fabric is constructed of multiple layers of yarns processed on a tricot warp knitting machine. The DBM fabric consists of layers of yarn and matt or nonwoven. The layers of yarn are held together by through-the-thickness (Z-axis) stitching yarns.

Fiberglass, aramid, and graphite-fiber reinforcement fabrics have been engineered on this process for use in composite parts and ballistic clothing. Yarns can be processed ranging in denier from 1800 to 20,000. Machine widths vary from narrow tapes to 72 inches and can be adjusted in one inch increments.

DB - DBM is a multipass technology system. Four layers of yarn individually oriented at specific angles, ranging from 30 degrees to 60 degrees, are introduced to the tricot stitching mechanism. This system allows yarns to be supplied in a linear or non-linear (zig-zag) fashion. The Z-axis yarns impale the layers, forming either a tricot or chain stitch. This fiber architecture can be processed through the tricot warp knitting machine several times to obtain up to eight layers of yarns. Each time a system of yarns is fed into the machine, it is stitched through-the-thickness with Z-axis yarns. This multipass technology yields a

higher degree of yarn impalement than the single pass.

Fabrics with a high degree of cover are possible on DB - DBM. Structures with high fiber volume and low porosity result. The eight layer stitching limitation of the machine achieves a maximum thickness of 1/8 inch. Machine speeds up to 700 rpm can be achieved. However, the multipass technology reduces the hourly production rate to 24 yards and increases the production overhead factor. Knitting machines with similar modifications cost close to $100,000.

Double Bias (DB) - Double Bias Matt (DBM)

Advantages

- Eight Yarn Layers, Can Incorporate Fiber Matt Into Bottom Layer
- Bias Angle Range Between 30 Degrees to 60 Degrees
- Up to 45 Yarns/Inch/Layer
- High Modulus Fibers in Yarn Layers
- Knitting Widths From Narrow Tapes to 72 Inches
- Fully Automated
- Low Incidence of Resin Rich Areas
- High Fiber Volume Percentages

Disadvantages

- Multi-Pass Highly Impaling Stitch Mechanism
- Z-Axis Cannot Stitch With High Modulus Fibers
- Lengthy Adjustments to Change Machine Knitting Width Between Production Runs Only
- 24 Yards/Hour Production/Machine
- Angle Change, Ply Orientation, and Width Change Are Not

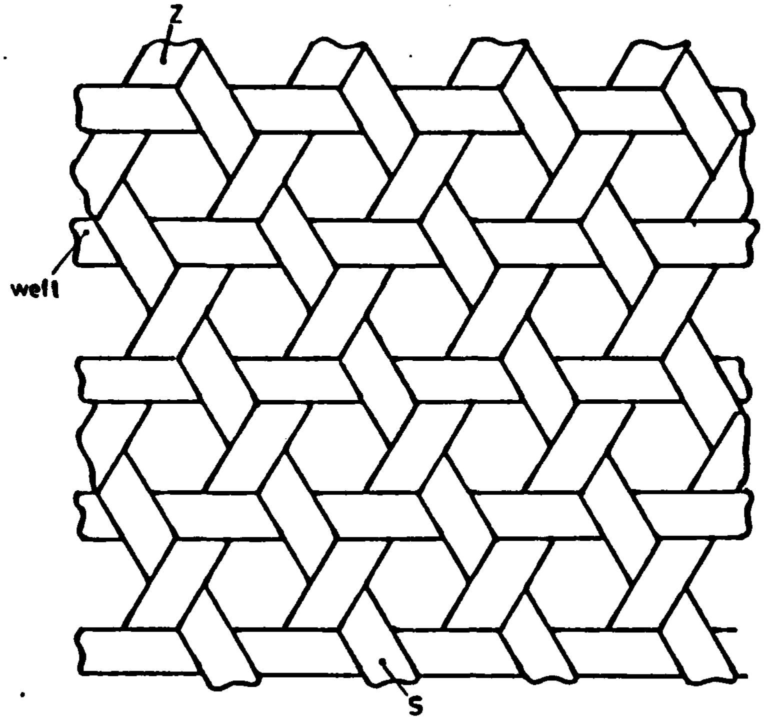
Automated

- Less Than 1/8 Inch Fabric Thickness
- No 3-D
- No Near-Net Shapes

E. NEXT GENERATION TRIAXIAL WEAVES:

Nonorthogonal interlaced structures have been produced for thousands of years. The Egyptians employed a nonorthogonal structure in basket weaving. A loom was developed in 1895 to weave nonorthogonal woven structures to be used as cane for chair bottoms. It wasn't until 1969 that a patent was issued to describe a continuous, nonorthogonal woven fabric. The "triaxial" fabric as termed by the inventor, Norris Dow, consisted of three, nonorthogonal planar yarn sets interlaced at 60 degrees respective to each other.

Triaxial woven fabrics are available in two weave constructions: the basic weave or open structure and the bi-plain weave or closed structure. Each of these structures is formed by the progressive interlocking of three yarns - Z warp, S- warp, and weft (Figure 26). In the basic weave, the Z-warp remains under the weft and over the S-warp throughout the entire constructional process. The S-warp is positioned over the weft and under the Z-warp (Figure 27). The opposite positioning relationship of the Z-warp and S-warp with the weft creates interlocking intersections, as opposed to interlaced. The almost perfect hexagonal voids formed at the interlocking intersections cause resin rich areas with relatively low fiber volume fractions.



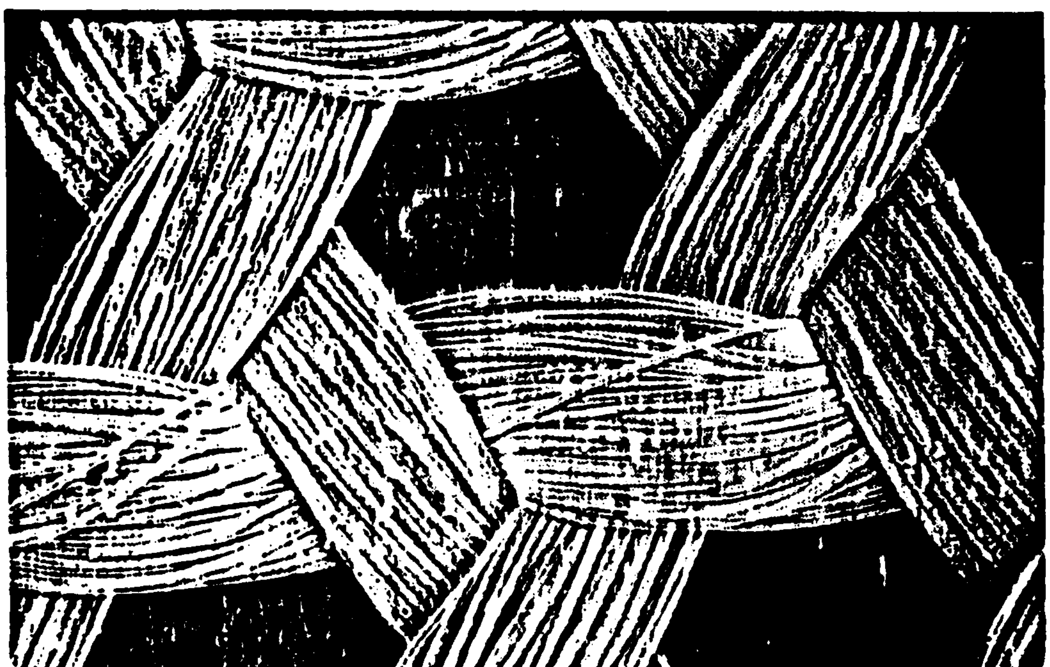
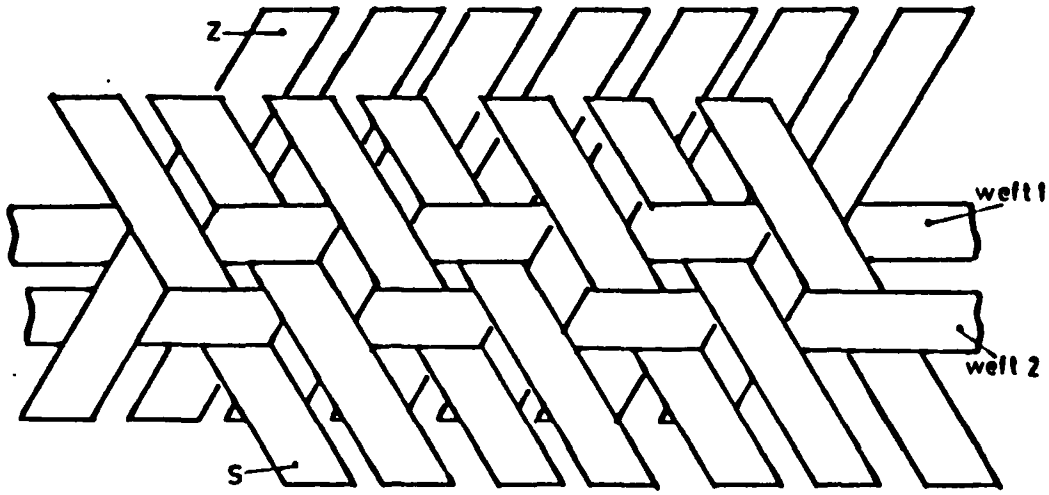


FIGURE 26 - BASIC TRIAXIAL FABRIC



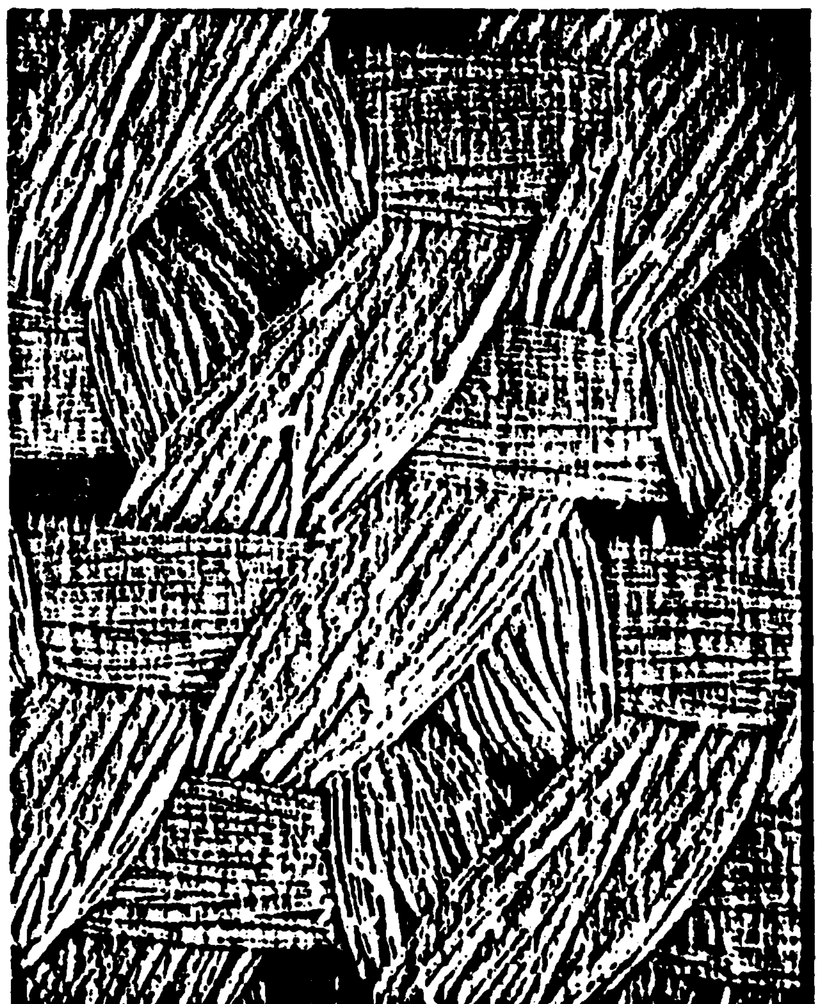


FIGURE 27 - BI-PLAIN TRIAXIAL WEAVE

The structure of the bi-plain triaxial weave yields a fabric with a higher fiber volume fraction but still less than 40%. The bi-plain fabric has been related to the double plain biaxial fabric in respect to the layering effect of the yarns. The Z-warp and S-warp alternate "over and under" positioning at each weft (Figure 27). This action allows for the three yarns to stack at each of the intersections. This layering effect enhances the fabric cover. The interlocking intersections of the bi-plain fabric create holes less pronounced than the basic weave triaxial fabric, yet apparent enough as voids to yield resin rich areas.

In 1972, Norris Dow and Barber-Colman, textile machinery manufacturer, collaborated to build an automated triaxial weaving machine. Several textile firms purchased the Barber-Colman machines; however, today, none of these are in operation. The voids created by the interlocking intersections and the triaxial machinery's inability to handle high-modulus fibers deemed it a "dead-end" in fiber preforms for composite applications.

A recent meeting with Norris Dow revealed the continuing efforts by Dick Dow in advancing the triaxial automated weaving machine. The new concept consisted of a loom that does not interlock yarn intersections and is capable of packing yarns as close as possible without interlacing. Concepts for fabricating interwoven or interlaced triaxial structures are also being explored.

<u>Triaxial Weaves</u>

<u>Advantages</u>

. Non-Orthogonal Structures

- High In-Plane Shear Resistance

<u>Disadvantages</u>

- No High Modulus Fibers
- Hexagonal Voids Cause Resin Rich Areas
- Low Fiber Volumes
- No 3-D
- No Multi-Layer Capability
- No Angle Variance From 60 Degree/60 Degree/60 Degree

V. EVALUATION OF TEXTILE FABRICATION TECHNIQUES:

State-of-the-art textile fabrication systems reviewed in the preceding pages offer unique capabilities for providing composite reinforcement of turbine components. None of the individual techniques possess the versatility to weave multi-layer, multi-angular, multi-dimensional fiber reinforced preforms. These technologies are essential to the future development of an "angular weaving" technique. Further discussion will cover the specific importance each technique possesses with respect to fabricating structural composite preforms for turbine component applications.

Multi-layer, multi-directional warp knits are produced by a variety of highly automated, production oriented methods. The resultant fiber architecture is composed of a system of weft (0 degree), warp (90 degree), and bias (+/-0) yarns stitched through-the-thickness with a chain or tricot warp knit stitch. MMWK fabrics vary in two major distinctions; linearity of bias yarns and the stitching mechanism. Each of these factors affects the resulting fabric mechanical properties.

Bias yarns may be placed in a linear or non-linear fashion. Orientation of parallel sheets of yarn in a non-linear fashion creates angle variance throughout the fabric (Figure 17). Specific angles are required in a preform to yield maximum strengths. Bending maximum strength and torque are achieved at 0 degree. Wherein twisting maximum strength and torque is seen at 45 degrees. Variations from these angles yields anisotrophy of mechanical properties. The linear placement of bias yarns

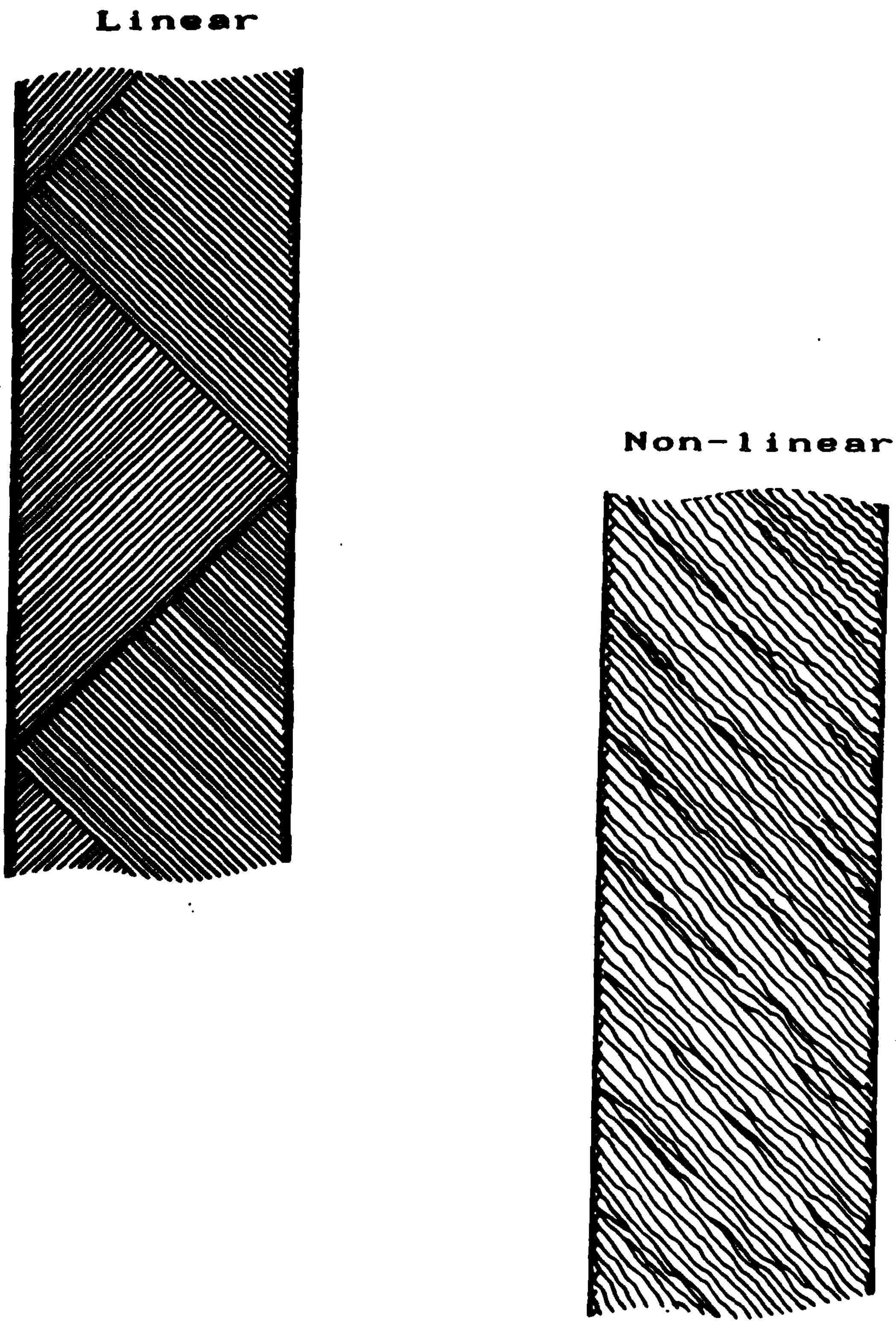


FIGURE 17 - LINEAR or NON-LINEAR YARN PLACEMENT

produces a fabric with more balanced directional properties than the non-linear yarn fabric. Controlled isotropy is a necessity in designing fiber reinforced preforms with tailored mechanical properties.

The stitching mechanism introduces the Z-axis through-the-thickness yarn reinforcement into the layers of yarn. This mechanism may be of two types; impaling and non-impaling. The impaling needles stitch through the fiber filaments causing fiber degradation. In the non-impaling stitch mechanism, needles carrying yarns, do not pass through or pierce one another, therefore no filament damage occurs. High modulus yarns must be accommodated gently through textile fabrication to insure good translation of mechanical properties.

The stitching mechanism affects the type of yarn that can be employed in the Z-axis direction of the fiber preform. The impaling stitch mechanism uses piercing needles. The action of the needles in penetrating through layers of yarns, requires that the yarns be very abrasion resistant. In multi-layer, multi-directional warp knits, the Z-axis yarns have been limited by this factor. Round hook needles stitch between layers of yarn in the non-impaling mechanisms (Figure 20). This results in less abrasion to the Z-axis yarns, but it also yields resin rich areas.

Stitch formation, whether chain or tricot, exerts bending and twisting forces on the Z-axis yarn. This requires that the Z-axis yarn have transverse and longitudinal strengths of near or equal value. It is commonplace that current high-modulus yarns yield much greater longitudinal strength than transverse strength.

Magazine Weft Insertion

Two Diagonal Yarn Arrangements

Stitch Construction

Warp Yarns

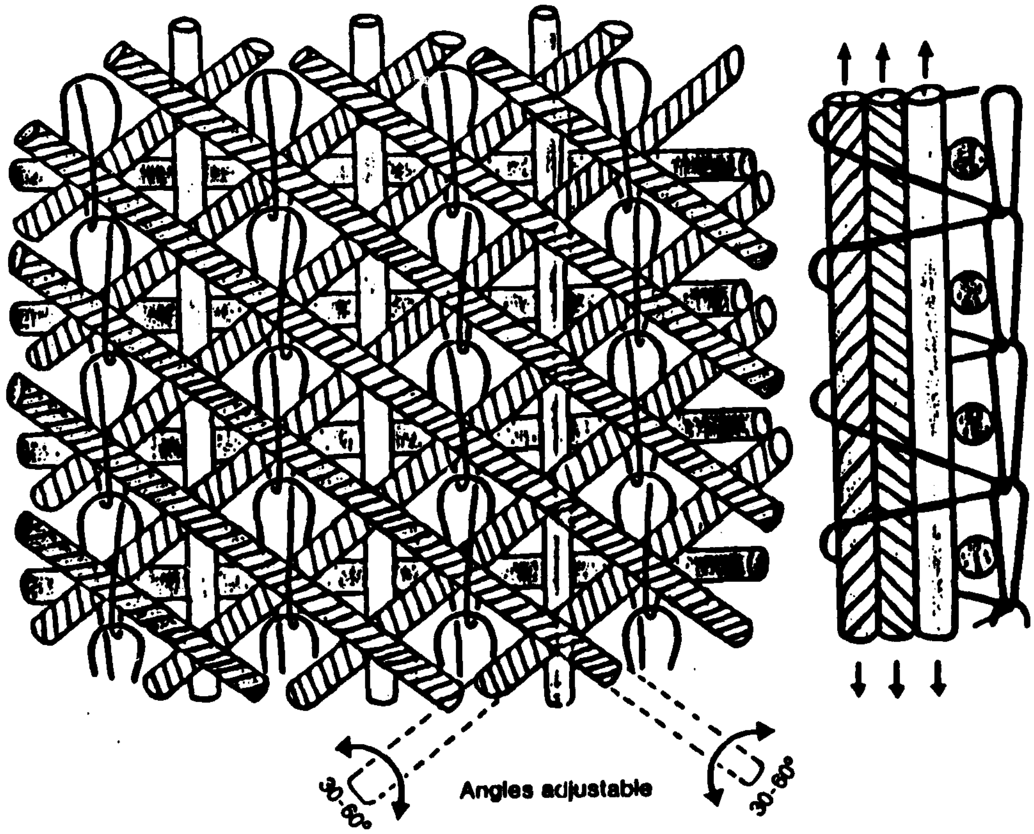


FIGURE 20 - MAYER RS 2 DS MULTI-AXIAL MAGAZINE WEFT INSERTION

This fact bars their use in the Z-axis direction. The Z-axis yarn providing reinforcement through-the-thickness improves impact and delamination resistance. This is best done, when the Z-axis yarn has similar mechanical properties to those yarns used in the x-y plane. This is not the case on current multi-directional warp knit machinery. These warp knits typically employ nylon or polyester multi-filament yarns as stitching yarns.

Multi-layer, multi-directional warp knits, whether with linear or non-linear bias yarns, impaling or non-impaling stitch mechanisms, do not currently possess the ability to construct multi-dimensional (greater than 2-D) composite fiber preforms. The double needle bar Raschel warp knitting machine can knit limited sized 3-D I-Beams. Size limitation of preform is directly related to the shogging motion of the lay-in yarn guide bar. A great deal of machine modifications would be required to create a 3-D fiber preform on the double needle bar Raschel with all-over off-axis fiber orientation in wide widths.

Present multi-directional weaving technology produces fabrics with fibers in three mutually perpendicular directions, x, y, and z. The AVCO BR900 and BR2000 3-D automated weaving machines fabricate near net-shape contoured preforms of high-modulus yarns. The high modulus yarns can be accommodated into the x, y, and z directions. The technique as it is represented today, does not typically introduce off-axis fibers into the structure. It is possible, with machine modifications to the winding step of the process, to obtain +/-45 degree yarn orientation. Currently, production has concentrated on fabricating near net-shape

contoured preforms with 0 degree/90 degree x-y fibers and z through-the-thickness fiber orientation.

Triaxial looms available on the market today have not proven efficient in weaving high-modulus yarns. The fiber architectures produced on this machinery with their inherent hexagonal voids would not prove suitable for most structural composite applications due to the inability of the structure to attain high fiber volume fractions.

Lappet weaving and Schiffli embrodiery systems provide technologies unusually applicable to angular weaving. The textile mechanisms involved in lappet weaving have the capability of handling high modulus yarns. This system is actually a combination of basic weaving and weft-inserted-warp-knitting (WIWK). Lappet's demise was the advent of warp knitted structures with multiple guide bars to selectively lay-in patterning yarns. Warp knits could be manufactured at much greater production speeds with extreme design versatility.

Lappet weaving is limited to 2-D capability. But this technology can be expanded to incorporate a system of whip threads for each layer or dimension of fiber architecture. Selective raising and lowering of warp yarns can avail a specific layer of yarns for whip thread insertion. Therefore, the potential exists for producing a 3-D composite preform with off-axis fiber orientation in select directions. The interweaving of the whip threads into the base fabric structure should be possible without the introduction of fiber degradation. Lappet weaving integrated into modern textile technologies could prove to be a major step

towards achieving true angular weaving.

Schiffli embroidery systems can provide multi-layer fabrics with off-axis fiber orientation. Current embrodiery technologies employ piercing needles to introduce the "embroidery" or patterning yarns. This technology is similar to the M.A.S.S. fabric in that plies are stitched together with piercing needles threaded with yarn. However, the embroidery Z-axis stitching yarn would also be oriented into the off-axis angle (Figure 7). This technology is not presently suited for high modulus yarns. Full scale embroidery production machines entail technology which could be of great importance to the weaving of 3-D composite preforms.

Jacquard technology surpasses harness weaving with its extended weave configuration capacity. To weave complicated structures, it is necessary to employ Jacquard systems that selectively control warp ends. A Jacquard is a head motion which can be applied to a shuttle or shutteless loom. Therefore, Jacquard is a sound alternative to a harness shedding motion with respect to its vast potential for fabricating complicated woven preforms for turbine engine components.

The evaluation of textile fabrication techniques available for use in the composites industry indicates a major shortfall in technology. Despite the wide array of technology available, it is not possible to produce a multi-directional, multi-angular, near-net shape fiber preform efficiently, in large quantities. The state-of-the-art fabrication process involves a series of value added processes starting with the production of the multi-filament

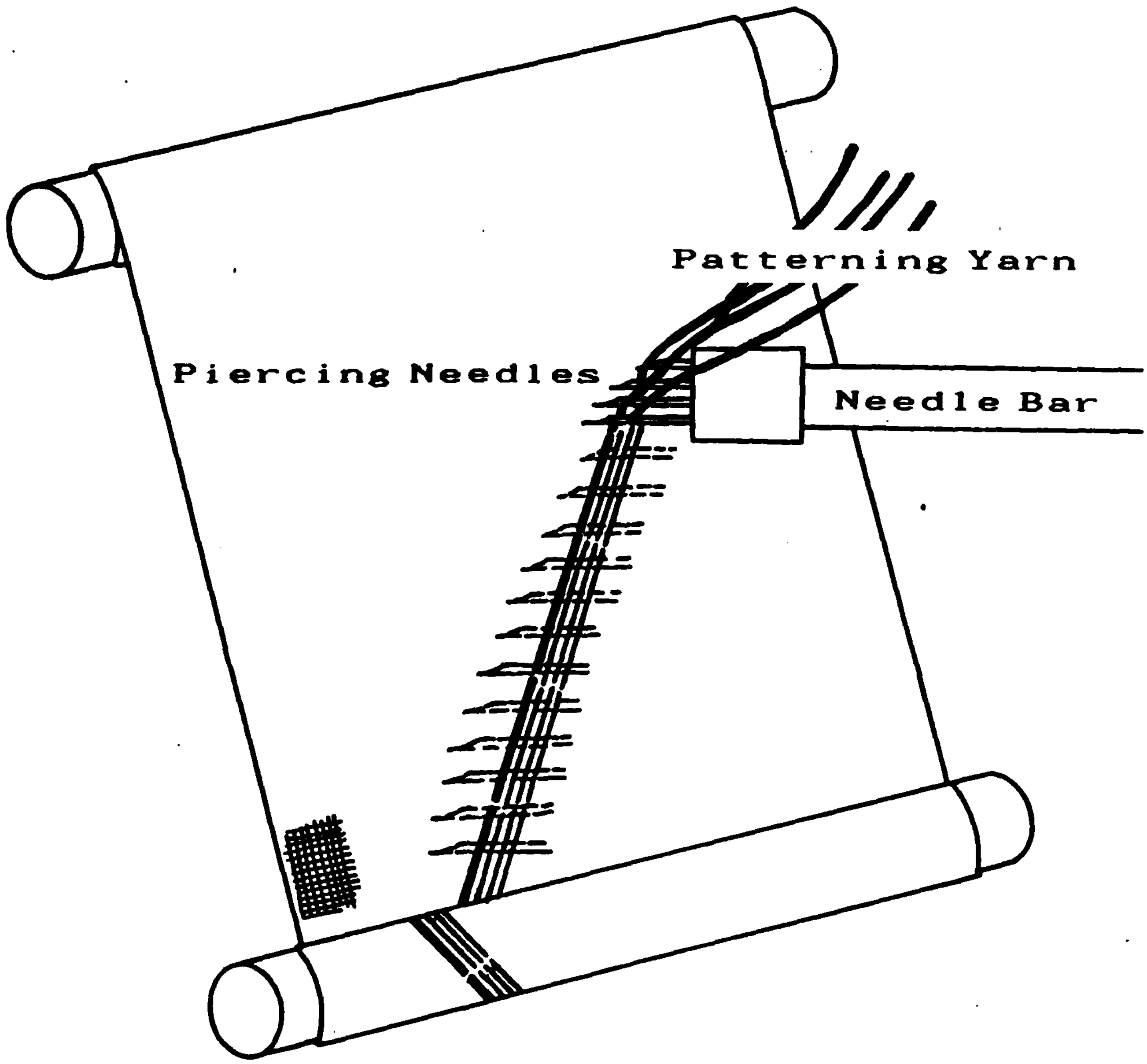


FIGURE 7 - EMBROIDERY FRAME

graphite fiber tow and proceding to flat 0 degree/90 degree fabric formation, fabric preimpregnation, manual laminate lay-up, and eventually culminating in part consolidation usually done in an autoclave. This process is fraught with expensive, risky, pitfalls. Prepreg fabric requires refrigeration and has limited shelf life. The major airframers have nightmares about huge shipments of prepreg sitting out in the hot Southern California sun only to become overaged, useless, tubes ready for the landfill. Ideally, it should be possible to develop a cost effective, high productivity, yarn positioning technique capable of supplying near net-shape fiber preforms ready for resin injection or transfer and final consolidation/curing.

State-of-the-art textile technologies, although not directly suited to the job at hand, do provide an excellent source of experience and equipment technology. From this base, it is conceivable that a solution can be found. Better said, it will not be necessary to "reinvent the wheel" only to use it in a novel way. Forgotten weaving systems such as Lappet weaving can be a source of extremely valuable technology.

VI. COMPOSITE TURBINE ENGINE COMPONENTS

In the course of completing this project, TTI studied the goals, approaches and progress that many firms have made in incorporating composite materials in turbine engine components. This study formed the basis for identifying the critical textile technology needs identified in the previous section. It was against these needs that a value assessment was made of the various weaving capabilities available in the marketplace.

In this section, two components which are prime candidates for conversion from metals to composites are identified. TTI worked with many fabricators in the course of this study and selected hardware made by a relatively local firm, Martin Marietta Aerospace of Baltimore, as target items. The items selected were a high temperature composite duct and a translating cowl. Both are items which compose parts of the engine nacelle (Figure 28). Both parts have been identified as excellent candidates for composite materials.

The thrust reverser translating cowl under study by Martin Marietta was the cowl for the CF6-80C2 high by-pass, turbofan aircraft engine. This engine incorporates the latest technology. It is powerful, light weight, and fuel efficient. Martin's first efforts to build a composite translating cowl were based upon the CF6-50 transcowl which was a good example of a refined aluminum aircraft structure, and a good departure point for initiating an advanced composite design.

The second item of interest is a thrust reverser precooler duct assembly. The existing duct is made of steel multi-stage

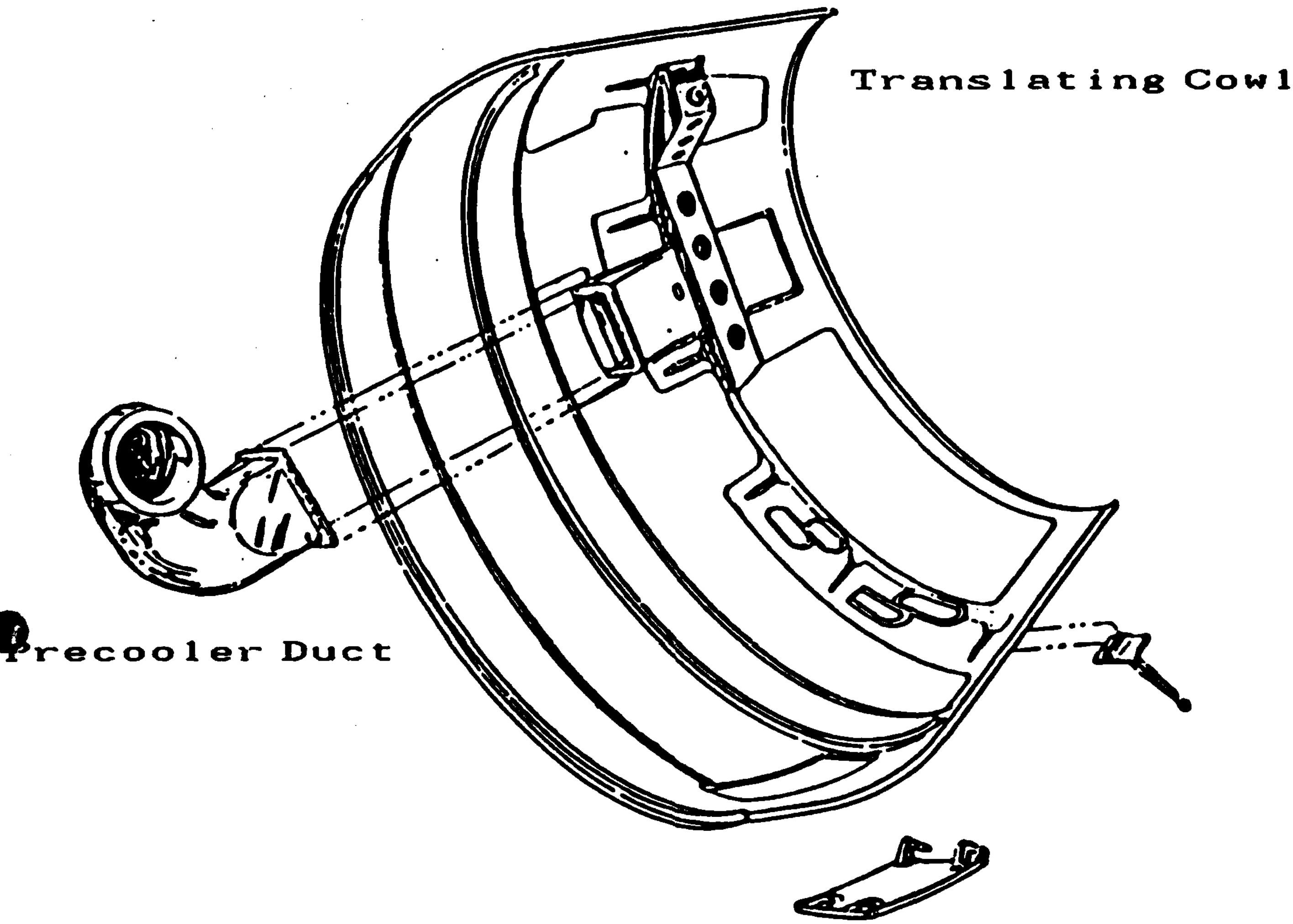


FIGURE 28 - THRUST REVERSER

drop hammmer components which are then trimmed and welded to form a complete duct including flanges and attachment brackets. This method of production requires a large number of tools including expensive drop hammer dies, trim tools, weld fixtures, check fixtures, etc., as well as the need to handwork parts to meet close tolerance design requirements. Studies at Martin determined that this duct could be fabricated out of advanced composites, in this case graphite/BMI and Nextel/BMI, in order to reduce weight, improve producibility, while actually reducing manufacturing costs.

Discussions with Martin's engineering staff identified the following generic requirements:

1) The ability to work with near-net shape preforms could greatly reduce the cost of manufacturing and increase the producibility of the cowl and the duct.

2) The preform would have to incorporate 0-90 degree and +/-45 degree fiber orientations in the same preform.

3) Fiber orientation control and fiber volume control would have to be exact.

4) Fiber damage due to handling would have to be minimized

5) Complex shapes such as stiffeners and flanges would be needed as well as flat sections.

A combination of the capabilities inherent in Lappett weaving equipment, state-of-the-art Conventional weaving systems and Jacquard harnessless control would provide technology adequate to satisfy the requirements. A loom combining these technologies would provide off-axis fiber orientation through the angular

weaving of yarns individually controlled such as to produce complex preforms.

In the case of the thrust reverser cowl, Martin desires to build structures where multiple layers of fabrics are used to sandwich a honey comb core. At present, each layer is cut from a sheet of prepregged graphite broadgoods. Each sheet is placed in a tool by hand, being careful to follow the desired fiber alignment/stacking sequence. Finally, the part is autoclaved to achieve consolidation of the laminates. This system is extremely labor intensive, involving excessive product handling, is prone to human error, and not well suited to high production rates due to the large amount of time required to produce each part. It would be far more effective to mechanically produce a multi-layer, multi-angular structure (Figure 29). A similar requirement is identified when looking at the multi-layer stiffeners widely used throughout the cowl. They, too, could conceivably be woven using this new, angular weaving loom. Impregnation could be accomplished using resin-transfer-molding (RTM) type [illegible] RTM is being closely examined as a possible cost [illegible] to impregnating composite structures for future [illegible] such as the LHX advanced helicopter.

The ducting system, identified as Item [illegible] from the hybridized loom proposed above. [illegible] of multiple layers of graphite/BMI [illegible] of Nextel/BMI used for fire protect[illegible] are all oriented as +/-45 degrees. [illegible] with flanges is required. [illegible]

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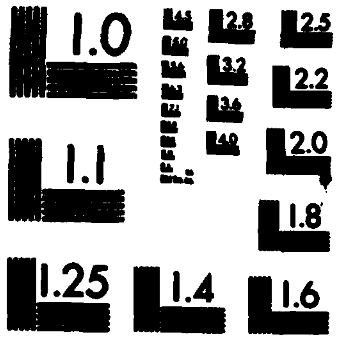

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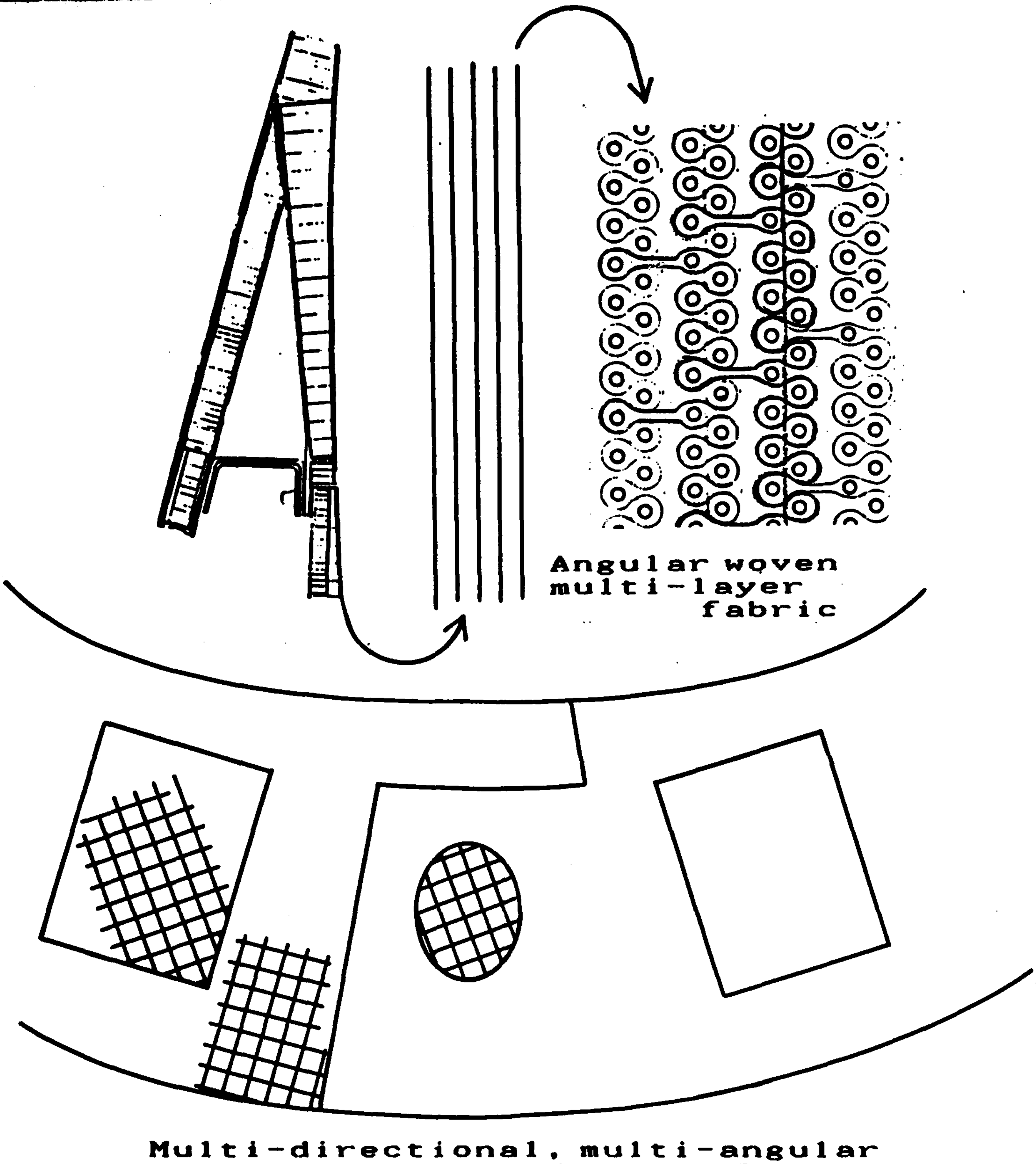

FIGURE 29-TRANSLATING COWL

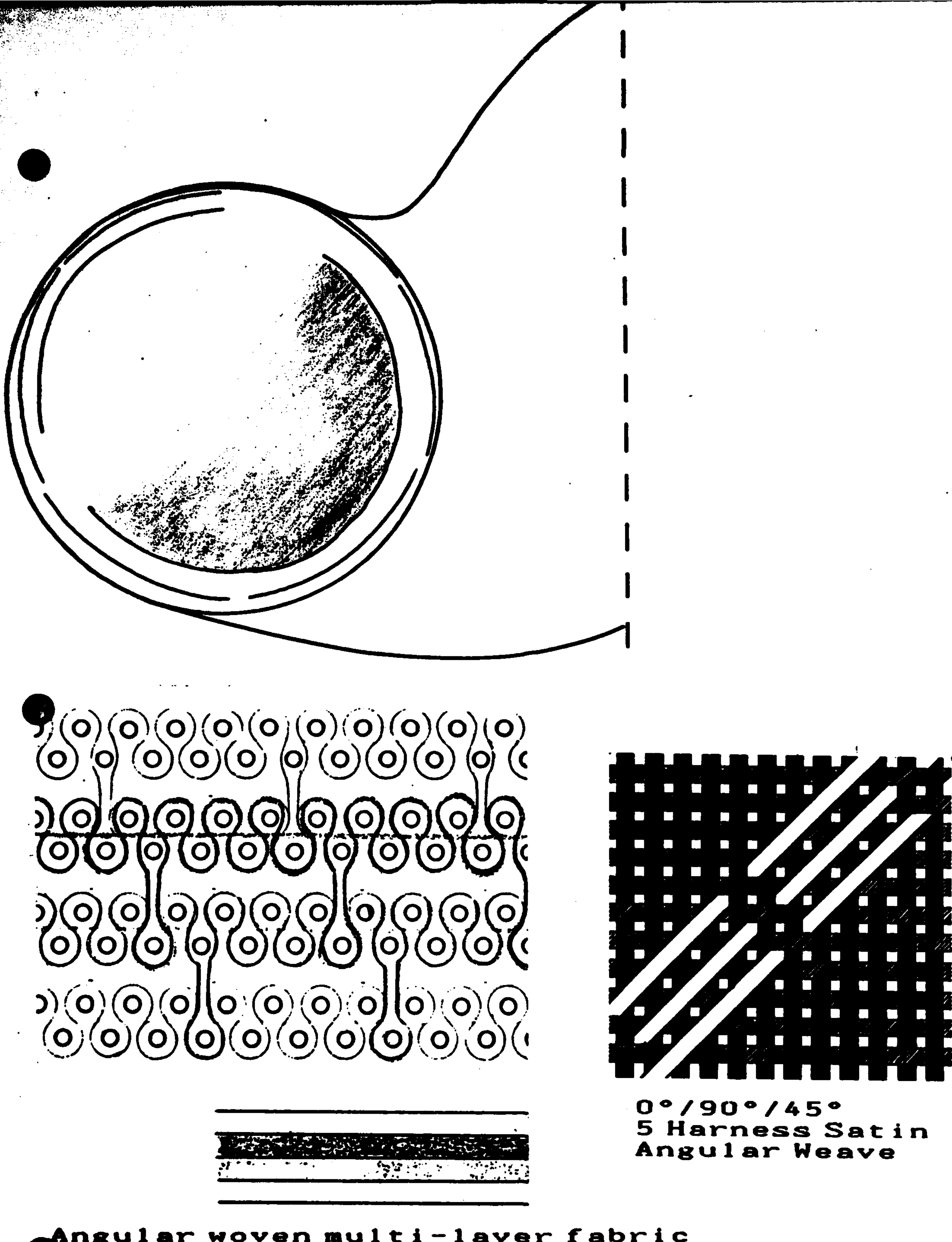

FIGURE 30 - PRECOOLER DUCT

requirements of the duct would be met by the Lappett weaving technology of the new angular weaving loom. The Jacquard head motion on the loom would satisfy the requirement to weave complex shapes with angular weaving.

Many other turbine engine components are under study by a number of manufacturers and government agencies as good candidates for replacement with composite materials. The two items above incorporate all of the generic requirements in light of fiber preforming. The proposed weaving system which combines Lappett, Jacquard, and state-of-the-art Conventional weaving technology in a unique way, offers a cost effective approach to the production requirements of each of the turbine engine parts in question.

VII. CONCLUSION

The textile technology industrial base of the United States encompasses a vast array of machines, looms, and weaving protocols. Very little of the energy and capital expended in developing this base has applicability to the weaving of reinforcements suitable for the production of advanced composite structures. Whereas, millions of dollars have been expended to develop equipment and procedure suited to the production of consumer textiles, for example, the marketplace could support such an expenditure. When Amoco expended millions to develop sixteen (16) foot wide shuttleless looms to produce polypropylene carpeting, they knew that they would eventually recover their investment many times over. This scenario has not occurred in the composites industry. In fact, until recently, very little attention was paid to the contributions of the textile industry to the fabrication of advanced composites.

This study identified the potential for advanced weaving protocol in the composites industry. The advanced turbine engine manufacturer has a need for composites in their future engines. They clearly state a desire or a need for fiber preforming technology, if they are to reach their goals.

TTI assessed the present ability of the textiles industry to meet the needs of the engine manufacturer and found a major shortfall. This shortfall is not a product of the inability of the industry to meet the challenge, but rather the result of a lack of interest on the part of both parties.

In an earlier section, it was stated that the engineering staff of one turbine engine component manufacturer, Martin Marietta, identified a series of generic requirements they would place on an idealized textile device:

1) Near-net shape weaving capabilities

2) Angular weaving capabilities

3) Exact control over yarn orientation and volume control

4) Minimal fiber degradation

The requirements are not presently achievable. But, it is clear that by properly organizing or combining a series of existing textile technologies, it will be possible to produce the angular woven, near-net shape preforms required to produce high quality, cost efficient turbine engine hardware.

An additional barrier that must be overcome if composite turbine engine components are to be fabricated, will be the necessity to impregnate these complex fiber architectures. The loom must be able to produce preforms which are compatible with state-of-the-art impregnation techniques. As referenced earlier in the report, "Clear lines of communication between the composite engineer and the textile engineer are necessary to successfully execute the fabrication of high quality, critical components". The textile engineer must, therefore, be careful not to design a loom that produces preforms which can not be impregnated.

Phase II of this program will involve the development of fiber architectures which can be effectively impregnated. Close coordination with leading composite processors will be necessary as will the fabrication of realistic structures as a means of evaluating the value of the fiber architecture. At the same time, the loom in question, will be developed under a separate project presently being evaluated by the Air Force. Both efforts must be closely coordinated to insure eventual success.

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